Performance Evaluation of Single Carrier 40-Gbit/s Downstream for Long-Reach Passive Optical Networks

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***Abstract*—This paper presents a new long reach PON (LR-PON) scenario operating at a single carrier of 40-Gbit/s for downstream, as an upgrade option of the LR-PON evolutionary strategy. An electrical 3-level duobinary modulation format was proposed for the 40-Gbit/s downstream transmission. In this paper the required optical signal to noise ratio (OSNR) and optical power budget were investigated based on analytic calculation of OSNR requirements and cascaded analysis with an optical link model. Numerical simulation results show that the 40-Gbit/s downstream operating at the wavelength of 1.5 µm can support a long reach up to 100 km and a high split ratio up to 256.**

***Index Terms*—Long reach passive optical networks, passive optical networks, optical fiber communications, performance comparison**

I. Introduction

THE demand for high bandwidth capacity of telecommunication networks is growing continuously. Among various access technologies, passive optical networks (PONs) are widely recognised as a cost-effective way to meet these bandwidth needs. Long reach PONs (LR-PONs) were later proposed as an economically viable solution, which increases the PON coverage span and the split ratio by employing optical amplifiers in the networks. LR-PON reduces the number of optical line terminators (OLTs) and consolidates network elements/nodes, thus resulting in significant energy reduction and cost savings. However, sharing a single LR-PON among more customers reduces the sustained available bandwidth, which requires increasing the data rate to support business-class applications or other bandwidth demanding services. The first demonstrated LR-PON named Super-PON [1] operated at 2.5 Gbit/s while covering a distance of 100 km and serving 2048 optical network units (ONUs). The PIEMAN [2] project has demonstrated a 10-Gbit/s LR-PON with a similar reach and a split factor of 512.

One way to further increase the capacity of the LR-PON in the downstream direction is to use wavelength stacking at 10-Gbit/s, similar to the time-and-wavelength division multiplexing PON (TWDM-PON) proposal of the next generation PONs (NG-PON2) [3]. As the bandwidth continues to scale up, however, this technique is clearly a compromise solution which achieves a higher aggregate rate by duplicating the terminal optical hardware. In this paper, as part of the evolutionary strategy for the LR-PON design, single carrier 40-Gbit/s downstream transmission with the electrical 3-level duobinary modulation is investigated as an upgrade option.

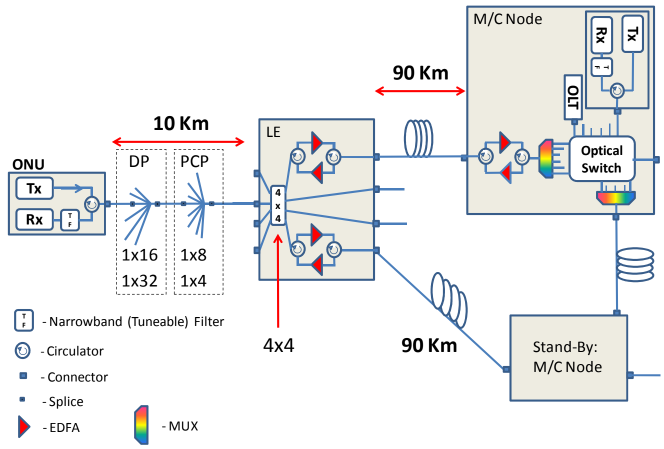

Fig. 1. Reference LR-PON architecture

The remainder of the paper is organized as follows. Section II introduces the LR-PON architecture under investigation and the proposal of the 40-Gbit/s downstream scheme with the 3-level duobinary and a bit-interleaving protocol. Section III investigates the optical signal to noise ratio (OSNR) requirements of the proposed 3-level duobinary modulation. Section IV presents the optical link model used for OSNR and optical power budget analysis. Simulation results are presented in Section V. Finally, Section VI concludes the paper.

II. LR-PON Architecture and Single Carrier 40Gbit/s Downstream Upgrade Scheme

The reference LR-PON design considered in DISCUS [4][5] is shown in Fig. 1. It shows a basic LR-PON architecture which bypasses old local exchange/central office (LE/CO) sites and terminates on the metro-core (M/C) nodes. Splitting points are located at the distribution points (DP), the primary cross connect (PCP), or the LE/CO site. The optical amplifiers are also situated in LE/CO, where electrical power is available. The optical distribution network (ODN) from the old LE/CO site is designed to support at least 10 km, while the feeder section has a distance up to 90 km with dual-homing protection shown in the figure.

The purpose of this paper is to investigate and evaluate an upgrade path which is able to deliver a higher serial data rate (>10Gbit/s) in the LR-PON configuration. Speed upgrade from 10 Gbit/s towards 40 Gbit/s is challenging as there are several significant technical issues related to this speed increasing:

- The distortion which is induced by chromatic distortion (CD) grows with the square of the bit rate. For a given transmission distance, a 40 Gbit/s system, which has 4x higher bit rate, is 16 times more susceptible to CD than a 10 Gbit/s system.
- To maintain the receiver SNR when increasing the bit rate by a factor of 4 requires nominally an increase of optical power of 6 dB. While APDs have been used extensively in 10Gbit/s PON downstream to improve the receiver sensitivity, no high-speed APD devices are commercially available for 40-Gbit/s NRZ operation.
- ONU electronics operating at the high line rate lead to further increase in power consumption. Considering the vast amount of subscribers, power consumption reduction in the ONU is of major importance.

For the 40-Gbit/s downstream transmission a 3-level electrical duobinary modulation scheme is proposed to reduce the optical bandwidth of the OLT transmitter and ONU APD receivers. Duobinary modulation relaxes the downstream channel bandwidth requirement to ~20 GHz thus improves the CD tolerance significantly compared to the NRZ format. This allows for 25-Gbit/s components (especially APDs) employed in ONUs, thus reducing the cost and power consumption.

CD was generally not an issue at 10Gbit/s rate for PONs. But it becomes a limiting factor when data rate further increases in combination with a longer reach. To extend the reach to 100km at 40 Gbit/s, the proposed scheme has to include a dispersion compensation element, such as a DCF or a fibre Bragg grating module at the OLT output. Because the DCF is shared between all users, it is not a cost-sensitive component. The extra insertion loss of DCF is of no issue as there is a downstream Erbium-doped fiber amplifier (EDFA) right before the trunk fibre (assuming insertion of DCF does not deteriorate the OSNR significantly).

Moreover, to further decrease the ONU power consumption, we propose a 40-Gbit/s bit-interleaving multiplexing PON (BiPON) scheme [6][7]. Theoretically, the lower limit of the ONU power-consumption is dictated by the actual user-rate, which typically is a fraction of the aggregated PON line-rate. While conventional TDM-PON protocols are inherently operating at line-rate, the proposed bit-interleaving ONU (Bi-ONU) takes advantage of the line-rate – user-rate discrepancy. In every frame period, the Bi-ONU decimates the downstream payload at a certain offset. Because the decimation takes place on bit-level, the hardware afterwards is working at the user rate, significantly decreasing the power consumption. In addition, BiPON protocol enables cost-effective implementation of advanced signal processing and FEC codes because the processing only needs to operate at the user rate.

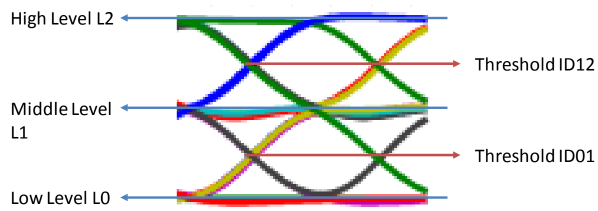

Fig. 2. Eye diagram and decision thresholds of 3-level duobinary signal

III. OSNR REQUIREMENTS FOR 40-GBIT/S 3-LEVEL DUOBINARY MODULATION

To determine the theoretical OSNR requirements for 3-level duobinary modulation, we first assume a downstream signal with a large amount of optical noise which is much larger than the ONU receiver noise. In this case the dominant noise terms will be optical beat noise terms: signal-spontaneous and spontaneous-spontaneous beat noises. Therefore, the mean-square noise current at the receiver has two noise terms [8],

$$\overline{i_{n,ASE}^2} = \Re^2 \cdot (2 P_S S_{ASE} + S_{ASE}^2 \cdot \Delta f) \cdot BW$$

where $\Re$ is reponsivity, P_S is signal power and S_{ASE} is optical noise density. Δf and BW are optical and electrical bandwidth respectively.

As illustrated in Fig. 2, the electrical duobinary signal eye-diagram has 3 distinct levels, which present three transmitted symbols S_0, S_1, and S_2. If we define the extinction ratio as the ratio between the high power level P_{S2} and the low power level P_{S0}, i.e., $re = P_{S2}/P_{S0}$, we find the following relationship for finite extinction ratio re,

$$\overline{P_S} = P_{S1}$$

$$P_{S2} = \frac{2 \cdot re}{1 + re} P_{S1}$$

$$P_{S0} = \frac{2}{1 + re} P_{S1}$$

As expected, the noise current on three levels is different and can be found as,

$$\sigma_0^2 = \overline{i_{n,ASE,0}^2} = \Re^2 \cdot (2 P_{S0} S_{ASE} + S_{ASE}^2 \cdot \Delta f) \cdot BW$$

$$\sigma_1^2 = \overline{i_{n,ASE,1}^2} = \Re^2 \cdot (2 P_{S1} S_{ASE} + S_{ASE}^2 \cdot \Delta f) \cdot BW$$

$$\sigma_2^2 = \overline{i_{n,ASE,2}^2} = \Re^2 \cdot (2 P_{S2} S_{ASE} + S_{ASE}^2 \cdot \Delta f) \cdot BW$$

where σ_0, σ_1 and σ_2 are the root-mean-square (rms) value of the noise currents.

At the receiver, an error will occur if the noise, at the sampling instant, is greater than the maximum allowed threshold level. We denote the error probability of receiving S_i when S_j was sent as,

$$P\{S_r = S_i \mid S_j\}$$

Also note that S_0 is sent with a probability of ¼, S_1 with a probability of ½ and S_2 with a probability of ¼. The overall error probability is given by,

$$BER = P_{e01} + P_{e12}$$

where

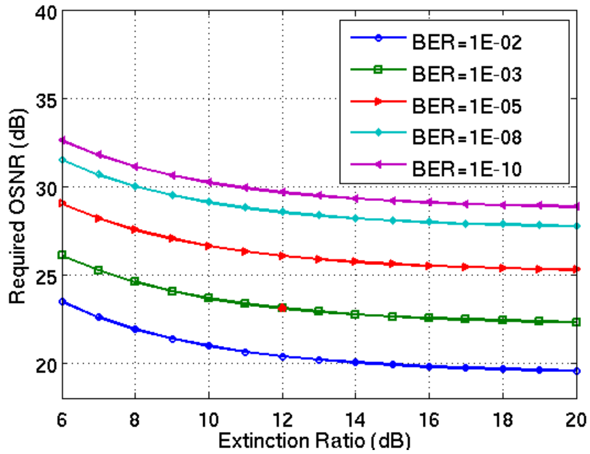

Fig. 3. OSNR requirement versus extinction ratio when 40-Gbit/s 3-level duobinary signal is generated at transmitter.

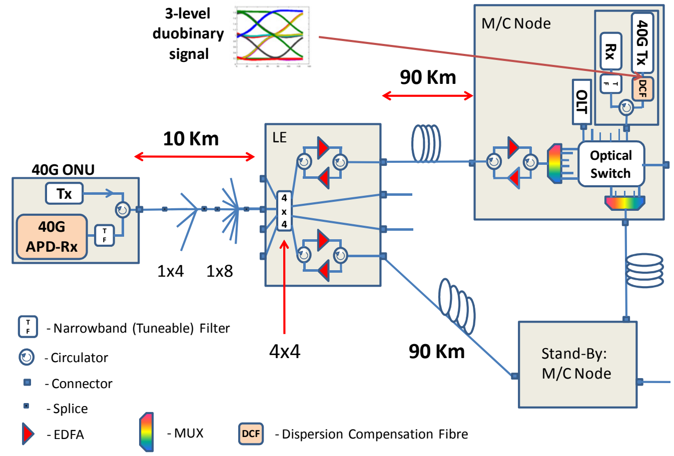

Fig. 4. 40-Gbit/s downstream path with 3-level duobinary modulation and APD receiver.

TABLE I
SET OF ASSUMPTIONS USED FOR 40-GBIT/S DOWNSTREAM POWER AND OSNR MODELLING

	Min. Loss (dB)	Max. Loss (dB)
DCF	5	5
Circulator	0.2	0.6
Connector	0	0.5
Fibre (per km)	0.2	0.3
Splice	0	0.3
1:2 Splitter	2.6	3.8
1:4 Splitter	5.4	7.1
1:8 Splitter	7.95	10.5
Mux/DeMUX	4	6
Optical Switch	1.8	2
Tuneable Filter	4	4

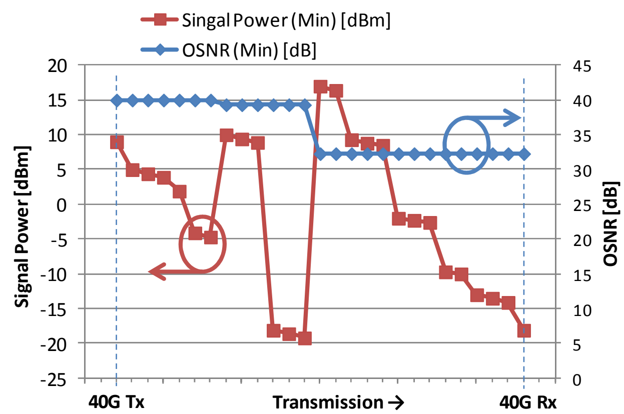

Fig. 5. 40-Gbit/s downstream analysis results in case of APD receiver for 90 km backhaul, 10 km ODN and 128-way split.

$$P_{e01} = \frac{1}{4}P\{S_r = S_1 \mid S_0\} + \frac{1}{2}P\{S_r = S_0 \mid S_1\}$$
$$= \frac{1}{4}\cdot\frac{1}{2}\mathrm{erfc}\left(\frac{I_{D01} - I_{S0}}{\sigma_0\sqrt{2}}\right) + \frac{1}{2}\cdot\frac{1}{2}\mathrm{erfc}\left(\frac{I_{S1} - I_{D01}}{\sigma_1\sqrt{2}}\right)$$
$$P_{e12} = \frac{1}{2}P\{S_r = S_2 \mid S_1\} + \frac{1}{4}P\{S_r = S_1 \mid S_2\}$$
$$= \frac{1}{2}\cdot\frac{1}{2}\mathrm{erfc}\left(\frac{I_{S2} - I_{D12}}{\sigma_2\sqrt{2}}\right) + \frac{1}{4}\cdot\frac{1}{2}\mathrm{erfc}\left(\frac{I_{D12} - I_{S1}}{\sigma_1\sqrt{2}}\right)$$

From these equations, we can see that the bit-error rate (BER) depends on two decision thresholds I_{D01} and I_{D12}. In practice, both decision thresholds should be optimized to obtain the minimum BER. By setting

$$d(P_{e01})/dI_{D01} = 0,$$

we can solve the optimal threshold that minimizes P_{e01},

$$I_{D01,opt} = \frac{1}{\sigma_1^2 - \sigma_0^2}\left[\sigma_1^2 I_{S0} - \sigma_0^2 I_{S1} + \sqrt{\sigma_1^2\sigma_0^2(I_{S1}^2 + I_{S0}^2) - 2\sigma_1^2 I_{S1}\sigma_0^2 I_{S0} + 2\sigma_1^4 \ln\left(\frac{\sigma_1}{2\sigma_0}\right)\sigma_0^2 - 2\sigma_0^4 \ln\left(\frac{\sigma_1}{2\sigma_0}\right)\sigma_1^2}\ \right]$$

The calculation of the second threshold $I_{D12,opt}$ results in a similar form.

Now with these equations in hand, we can estimate the required OSNR for a given BER threshold. Fig. 3 shows the OSNR requirement versus extinction ratio for various BER thresholds with above assumptions.

For example, given an optical bandwidth of 12.5 GHz (0.1nm bandwidth at λ = 1.55 μm), an electrical bandwidth of 20 GHz, extinction ratio of 12 dB, the required OSNR is about 23.1 dB for BER=1E-3. This is the case when the 3-level duobinary signal is generated by the downstream transmitter.

IV. POWER BUDGET AND OSNR MODELLING

This section presents the power and OSNR modelling for two different topologies: the first one with a 20GHz APD receiver and the second one with an SOA-preamplified PIN receiver.

A. 40Gbit/s downstream using 3-level duobinary modulation and APD-Rx

Fig. 4 shows the 40Gbit/s downstream topology with the 3-level duobinary modulation scheme. The losses of various components used in the modelling have been summarised in TABLE I. Given the optical power requirement of 40-Gbit/s downstream, we assume a high power local exchange (LE) downstream EDFA with +17 dBm output power and an EDFA

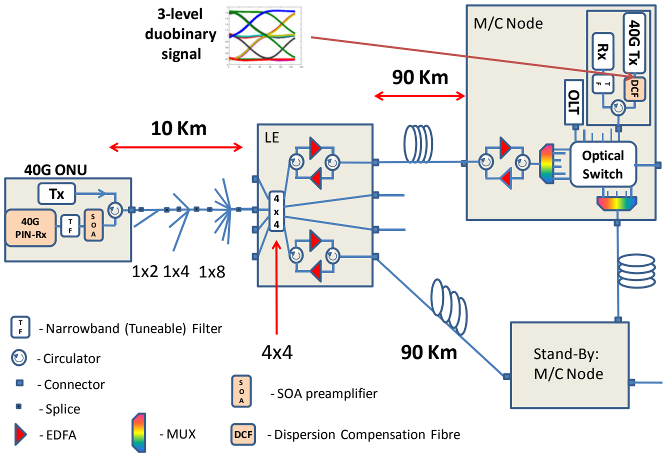

Fig. 6. 40-Gbit/s downstream path with 3-level duobinary modulation and SOA-PIN receiver

TABLE II
OPTICAL POWER MARGIN FOR 40-GBIT/S DOWNSTREAM WITH APD RECEIVER

	Standard FEC (pre-FEC BER=1E-3)	Strong FEC (2dB improvement)
256 split	1.75	3.75
512 split	Negative margin	0.7

in metro/core (MC) node with +10 dBm output power. Both EDFAs have a noise figure of 5.5 dB.

Here we assume a 20-GHz APD receiver is used in 40-Gbit/s ONU and a high power optical transmitter with +9dBm output power is used at the 40-Gbit/s OLT. Fig. 5 shows the 40-Gbit/s downstream analysis in terms of power and OSNR budget for a 90 km backhaul, a 10 km ODN and a 128-way split. Given the TX output power, the derived optical gains are 14.7 dB and 36.2 dB for the downstream MC node EDFA and the LE EDFA respectively. As we do not have an optical pre-amplifier in front of the downstream Rx the architecture will not be limited by the OSNR. This assumption is confirmed by the estimated OSNR (~32.3 dB), which is sufficiently high for 40Gbit/s 3-level duobinary operation. Therefore, the relevant parameter is the input optical power. The minimum received signal power at APD input is -18.1 dBm and the receiver needs a dynamic range of more than 11.4 dB to avoid overloading.

Since FEC is commonly employed in 10G-class PON systems to improve the optical link budget, we assumed a similar pre-FEC BER threshold of 1E-3 for the sensitivity estimation. For a BER of 1E-3, the APD receiver sensitivity for 40-Gbit/s duobinary signal is assumed to be -19.5 dBm. Because of the bit-interleaving protocol, the downstream FEC decoder will work at much lower user rate, making more complex FEC codes feasible in ONUs. Therefore, if a strong FEC, such as low-density parity-check (LDPC) codes, would be used, it would give us some extra margin due to a higher pre-FEC BER [9].

This leads to the optical power margin shown in TABLE II, assuming 2 dB sensitivity improvement by using a strong FEC.

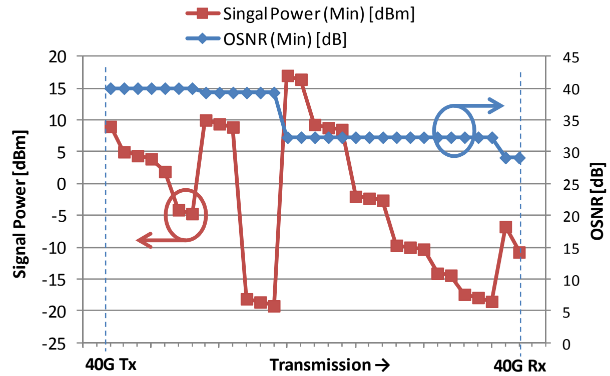

Fig. 7. 40-Gbit/s downstream analysis results in case of SOA-PIN receiver for 90 km backhaul, 10 km ODN and 256-way split.

TABLE III
OPTICAL POWER MARGIN FOR 40-GBIT/S DOWNSTREAM WITH SOA-PIN RECEIVER

	Standard FEC (pre-FEC BER=1E-3)	Strong FEC (2dB improvement)
256 split	1.75	3.75
512 split	Negative margin	0.7

B. 40Gbit/s downstream using pre-amplifier SOA in ONU

In order to improve the optical budget, a semiconductor optical amplifier (SOA)-preamplifier with a PIN ONU receiver can be employed, as shown in Fig. 6. The compact size and integrability of the SOA makes it a suitable candidate for the use as optical preamplifiers in ONU. But it usually has a higher inherent noise figure than EDFA. In the following power and OSNR analysis, an SOA with a noise figure of 7.5dB and maximum power gain of 12dB is assumed. As the gain of the SOA can be controlled by changing the bias current, the maximum gain assumption is applied here to lower the power consumption of ONUs. In the analysis, the real power gain of the SOA is derived on condition that the PIN-Rx is not overloaded (i.e., +3dBm at the input of the PIN-Rx). The other assumptions are the same as previously discussed and summarised in TABLE I.

Fig. 7 shows the 40Gbit/s downstream analysis using a combination of an SOA and a PIN-Rx for a 90km backhaul, a 10km ODN and a 256-way split. Given the TX output power of +9 dBm, the derived optical gains are 14.7 dB and 36.2 dB for the downstream MC node EDFA and the LE EDFA respectively. The gain of the ONU SOA is calculated as 11.3 dB, which is smaller than the maximum optical gain assumption of 12 dB. The power and OSNR results suggest that the downstream is still not limited by the OSNR (minimum 29.1 dB) and the limitation comes from the receiver input optical power. In this case, the minimum received signal power at PIN-Rx input is -10.75 dBm and the receiver needs a dynamic range of more than 13.75 dB to avoid Rx overload. We assume the PIN receiver sensitivity for 40-Gbit/s duobinary signal is -12.5 dBm for BER=1E-3. The resulting optical power margins are shown in TABLE III, again assuming 2 dB sensitivity improvement by using a strong FEC.

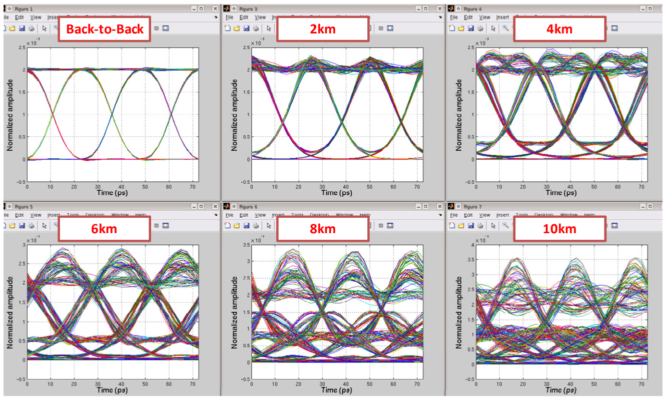

Fig. 9. Eye-diagram of 40Gbit/s NRZ for various reaches

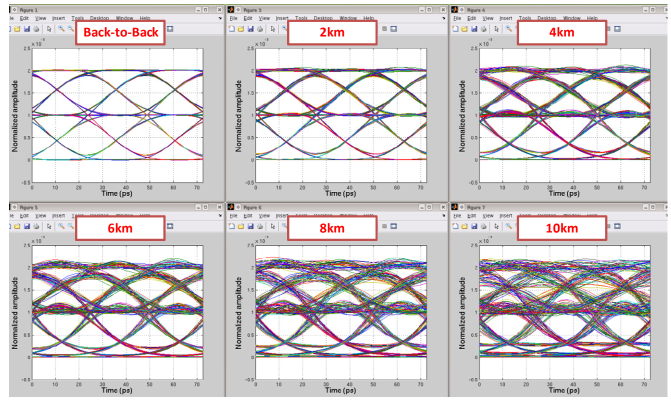

Fig. 8. Eye-diagram of 40Gbit/s 3-level duobinary signal for various reaches

TABLE IV
SIMULATED DISPERSION POWER PENALTY

	Dispersion Power Penalty (dB)	
Distance (km)	40G NRZ APD-Rx	40G 3-level duobinary APD-Rx
2	0.1	0.1
4	0.5	0.6
6	3.1	1.3
8	Does not work	2.6
10	Does not work	5.8

V. 40GBIT/S DOWNSTREAM SIMULATION RESULTS

One advantage of the 3-level duobinary modulation over NRZ modulation is its better chromatic dispersion tolerance. For example, a 26-Gbit/s transmission over 40 km has been demonstrated using duobinary detection at λ=1314 nm [10]. To emulate this technology for the DISCUS LR-PON, the proposed 40Gbit/s downstream architecture has been simulated using a system simulator built with RSoft Optsim and Matlab. Because a dispersion compensation module is included at the output of the OLT to compensate the common optical path, i.e. backhaul, the maximum differential reach is 10km in the access section. The simulated eye-diagrams of 40Gbit/s NRZ for 0, 2 km, 4 km, 6 km, 8 km, and 10 km reaches are shown in Fig. 9. It can be noted that the NRZ eyes are getting really closed after reach of 6km. As a comparison, the eye-diagrams of 40-Gbit/s 3-level duobinary signal for 0, 2 km, 4 km, 6 km, 8 km, and 10 km reaches are shown in Fig. 8. Even at 10 km reach, a 3-level signal is still able to be recognised from the eye-diagram.

In order to illustrate the benefit of choosing 3-level duobinary modulation, we have simulated the impact of chromatic dispersion using Monte-Carlo techniques. Specifically, we have run simulations of both 40-Gbit/s NRZ and 3-level duobinary system for different fibre lengths and observed the power penalties with respect to their back-to-back cases. We assumed APD receivers used and a pre-FEC BER threshold of 1E-3 for sensitivity penalty calculations. The resulting power penalties for these two modulation formats are listed in TABLE IV. The 40-Gbit/s NRZ signal cannot meet pre-FEC of 1E-3 when the transmission length is higher than 6km. Furthermore, at transmission length of 6 km, the power penalty of 40-Gbit/s 3-level duobinary transmission is much smaller than that of 40-Gbit/s NRZ signal (1.3 dB versus 3.1 dB).

Given a differential reach of 10 km, the nominal dispersion length should be chosen as the mean of the distance of the shortest and the longest reach. For the 40-Gbit/s architecture discussed so far, the shortest reach is 90 km and the longest is 100 km. Thus the dispersion compensation element should compensate about 95km of fibre, which leaves uncompensated length of ±5 km. In the following analysis, we will assume that system margin should be larger than the dispersion power penalty for 6 km reach (i.e., 5 km plus 1 km extra margin assumed).

Similar simulation has been done for the SOA-PIN receiver using 3-level duobinary modulation, assuming optical noise is negligible. At a distance of 6 km, the dispersion penalty is about 0.9 dB instead of 1.3 dB for the APD receiver.

Taking the power margins shown in TABLE II and TABLE III, the dispersion penalties at 6 km for both the APD and the SOA-PIN receivers should be subtracted to evaluate the final system margin. Therefore a 40-Gbit/s APD receiver using 3-level duobinary can barely support 100 km reach and 128-split all together (only 0.1 dB margin). If we use a strong FEC, assuming 2 dB sensitivity improvement, the power margin would be 2.1 dB. On the other hand, the SOA-PIN receiver can be used in the ONU to achieve a split ratio up to 256, having a margin of 0.85 dB with a standard FEC and 2.85 dB with a strong FEC.

VI. CONCLUSION

As part of the evolutionary strategy, 40-Gbit/s transmission in the downstream direction is investigated as an upgrade option. To upgrade to a single-carrier 40-Gbit/s downstream in LR-PONs, a 3-level duobinary modulation scheme with downstream BiPON protocol is proposed. The 3-level duobinary relaxes the component bandwidth requirement at ONU and shows better tolerance for chromatic dispersion. The BiPON protocol would further reduce the power consumption and enable cost-effective implementation of advanced FEC codes because the FEC decoder only needs to operate at the user rate. The 40-Gbit/s downstream topologies with APD and

SOA-PIN receivers have been analysed in terms of power and OSNR budget. Assuming a strong FEC with a 2 dB power budget improvement, an APD receiver would support a 90km backhaul, a 10 km ODN and a 128-way split while a SOA-PIN receiver would allow for an upgraded split ratio of 256 at 40 Gbit/s.

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