Polarization mode dispersion compensation for the South African optical-fibre telecommunication network

T.B. Gibbon*, **L. Wu***, **D.W. Waswa***, **A.B. Conibear*** **and A.W.R. Leitch***‡

Polarization mode dispersion (PMD) is worldwide a major obstacle in the successful implementation of next-generation optical-fibre telecommunication networks. Countrywide PMD measurement results are presented which illustrate the extent of the PMD problem in the South African network. An analysis of these results highlights the urgent need for a suitable intervention strategy such as PMD compensation if the South African network is to operate extensively at 10 Gb/s and beyond. The effectiveness of a number of established PMD compensation techniques is demonstrated experimentally using PMD compensators which we built and tested. Furthermore, investigations into the stability of PMD in deployed fibre networks under local conditions illustrate how PMD gradually drifts in buried fibre, and rapidly fluctuates in aerial fibre. These results confirm that PMD compensation is extremely difficult in aerial fibre due to the need to track the rapid PMD fluctuations continuously in real-time. We also briefly discuss possible alternative strategies besides PMD compensation for dealing with the PMD problem in the South African network.

Introduction

In order to meet ever increasing communication and information sharing demands, there is currently a global trend towards the upgrade of existing optical-fibre networks to operate at bit rates of 10 Gb/s, 40 Gb/s and above. Polarization mode dispersion (PMD) is currently a major obstacle in the successful implementation of these next-generation networks. The severe restrictions imposed by PMD apply to networks worldwide, a problem compounded by the fact that PMD compensation is extremely difficult. Since much of the South African network consists of high-PMD legacy fibre, it is important to investigate the effectiveness and merits of various PMD compensation and mitigation strategies if the South African network is to be upgraded to operate extensively beyond 2.5 Gb/s, which it is currently unable to do in support of extensive long-haul transmission.

Polarization mode dispersion describes the deleterious combined effects of birefringence and mode coupling, which are unavoidably introduced during the fabrication, cabling and deployment of optical fibre. Light propagating within a single mode optical fibre does so as the linear superposition of two orthogonal HE_{11} polarization modes.[1] Birefringence introduces a difference in the group velocities of the two polarization modes, which in turn gives rise to a dispersive broadening of the output pulse as illustrated in Fig. 1. The difference in the times of flight of the two polarization modes through the fibre is called the differential group delay (DGD). Both the DGD and the principal states of polarization (the pair of polarization states corresponding to the fast and slow birefringent fibre axes) vary as a function of wavelength due to mode coupling introduced by variations in the birefringence along the length of the fibre.[2] The first-order PMD at any particular wavelength is completely characterized by the DGD and the principal states of polarization (PSPs) at that wavelength. As such. it is useful to represent the first-order PMD by

$$\vec{\tau} = \Delta\tau\hat{q}, \qquad (1)$$

where $\Delta\tau$ is the DGD, and $\hat{q}$ is the unit vector pointing in the direction of the slow PSP in Stokes polarization space.[3]

Should the DGD exceed a significant fraction of the transmission bit period, then the resultant power fading and inter-symbol interference associated with the broadening of the output pulse causes network outage. The effects of PMD are complicated by the fact that the birefringence and mode coupling vary randomly with time under the influence of changing environmental conditions. The variability in PMD with both time and with wavelength makes PMD compensation notoriously demanding.

In this paper we begin by presenting an analysis of PMD measurement results which reveals the extent and implications of the PMD problem in the South African network. These results highlight the relevance and importance of PMD compensation. We discuss several established PMD compensation methods and illustrate their effectiveness using PMD compensators which we built and tested. Results from investigations into the response time requirements for PMD compensators to track PMD fluctuations in deployed fibre are presented. The merits of several PMD mitigation strategies and alternatives to PMD compensation are then considered.

Polarization mode dispersion compensation

The need for PMD intervention in the South African network

Figure 2 summarizes the results of interferometric PMD measurements on deployed fibre from five different regions across South Africa, as performed by our group between 2002

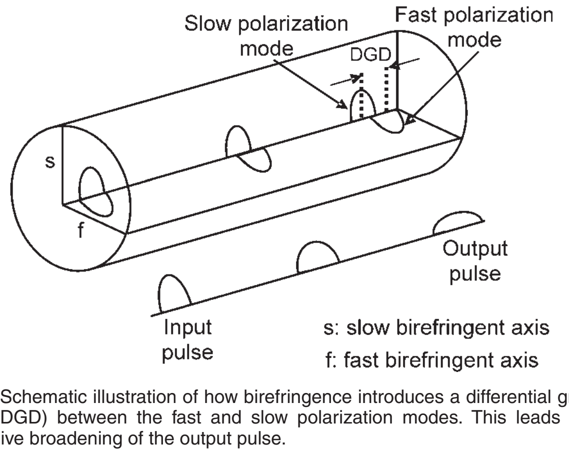

Fig. 1. Schematic illustration of how birefringence introduces a differential group delay (DGD) between the fast and slow polarization modes. This leads to a dispersive broadening of the output pulse.

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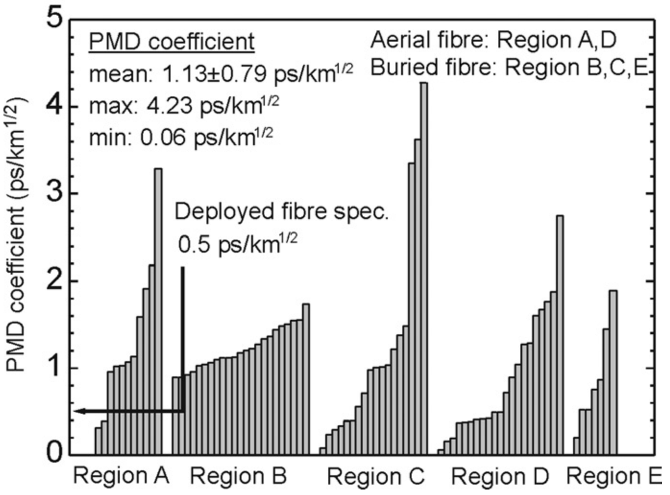

Fig. 2. The results of PMD measurements performed across South Africa. Seventy-five per cent of the fibres tested exceed the maximum PMD coefficient specification of 0.5 ps/km$^{1/2}$.

and 2005.[4] In long lengths of single-mode fibre, mode coupling causes the PMD to be proportional to the square root of the fibre length. The PMD values in Fig. 2 are thus reported as PMD coefficients, which are the PMD values in picoseconds normalized to the square root of the fibre lengths. Also indicated in Fig. 2 is the generally accepted PMD coefficient specification of 0.5 ps/km$^{1/2}$ for deployed single-mode fibre. The PMD coefficient of deployed fibre should ideally be far less than 0.5 ps/km$^{1/2}$, especially for networks operating at 40 Gb/s and above.

From this representative sample of 80 buried and aerial links tested, only 25% (20) have a PMD coefficient within the 0.5 ps/km$^{1/2}$ specification. In order to put the results of Fig. 2 in perspective, it is useful to consider an estimate of the maximum network reach as a function of PMD coefficient for various network designs, as shown in Fig. 3. For example, it is evident from the figure that with the non-return-to-zero (NRZ) modulation format and a 1 dB power penalty (the extra power margin allocated to overcome PMD), a fibre with the national average PMD coefficient of 1.13 ps/km$^{1/2}$ can only support transmission up to 35.4 km at 10 Gb/s, and 2.2 km at 40 Gb/s. In general the maximum network reach depends on a number of network design parameters such as the power penalty allocated to PMD (typically ε = 1–2 dB), the acceptable outage probability (typically P_{out} = 10^{-4}–10^{-9} depending on the application), the modulation format, and the properties of the transmitter/receiver pair.[3] It must be noted that the maximum transmission distances displayed in Fig. 3 are only estimates, since factors such as the second-order PMD (the change in PMD with wavelength) and the PMD contribution of network components (such as erbium-doped fibre amplifiers, and multiplexers) are not taken into account.

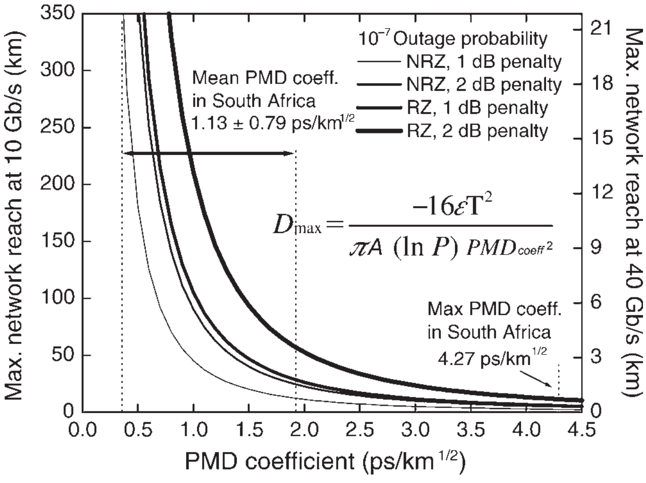

Fig. 3. Estimates of the maximum network reach (D_{max}) at 10 Gb/s and 40 Gb/s for different network designs without PMD compensation. Receiver parameters of A = 30 and A = 70 were used for return-to-zero (RZ) and non-return-to-zero (NRZ) modulation formats, respectively. The bit period for 10 Gb/s and 40 Gb/s transmission is T = 100 ps and 25 ps, respectively.

In a country as geographically large as South Africa, extensive long-haul transmission is crucial. From Figs 2 and 3 it is evident that the restrictions imposed by PMD render the South African network currently unable to support extensive long-haul transmission beyond 2.5 Gb/s. Uncompensated long-haul 10 Gb/s transmission is possible in certain low-PMD sections of the South African network, provided that optimal network design is exercised. At 40 Gb/s, however, PMD compensation throughout the network would be a necessity for both long-haul and shorter transmission distances. It is thus worth investigating the possibility of implementing a PMD compensation solution at 10 Gb/s, which is upgradeable to 40 Gb/s.

Optical PMD compensation strategies

There are essentially three cornerstone optical first-order PMD compensation strategies, namely, PSP transmission, fixed-delay PMD compensation, and PMD nulling. PSP transmission was one of the very first PMD compensation strategies to be proposed and experimentally demonstrated.[5,6] Sometimes referred to as pre-transmission PMD compensation, this approach makes use of a polarization controller situated at the beginning of the link to continuously track the changing PMD of the link by aligning the input state of polarization (SOP) of the transmitted signal with either the fast or the slow PSP. With the signal confined entirely to a single PSP, the light wave propagates as a single polarization mode and no dispersive broadening of the pulse due to PMD can occur. The drawback of this approach is that the compensation control speed and convenience is limited by the need to transmit monitoring information continuously from the receiver end of the link to the beginning of the link in order to adjust the polarization controller so as to track the changing PMD of the link.

Post-transmission compensation techniques such as fixed-delay PMD compensation and PMD nulling are more convenient to implement as the compensation process is confined entirely to the output end of the link. For fixed-delay PMD compensation a polarization controller followed by a birefringent delay element with fixed delay (typically a length of polarization maintaining fibre) are placed directly after the link. This is schematically represented in Fig. 4, where $\vec{\tau}_{link}$ and $\vec{\tau}_c$ represent the PMD vectors of the link and fixed-delay compensator, respectively. A small fraction of the signal (typically 5–10%) is tapped before the receiver and used to monitor and control the PMD compensation process. In our investigations, a polarimeter was used to monitor the degree of polarization (DOP) of the

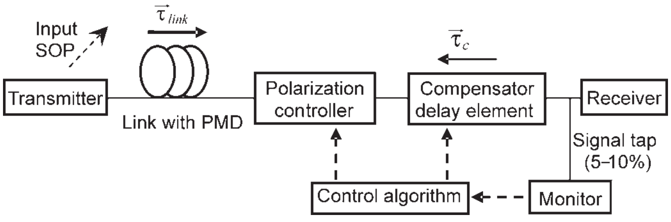

Fig. 4. For fixed-delay PMD compensation and PMD nulling, a polarization controller followed by a delay element is placed directly after the link. A signal tap is used to monitor and control the compensation process.

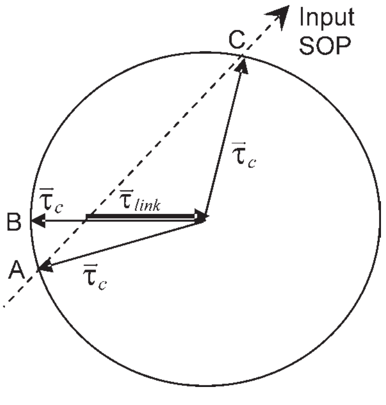

Fig. 5. A two-dimensional Stokes space representation of PMD compensation, where $\vec{\tau}_{link}$ and $\vec{\tau}_c$ represent the PMD vectors of the fibre link and the PMD compensator, respectively.

signal. Since the presence of PMD depolarizes a light wave signal, adjusting the PMD compensator settings in a feedback fashion so as to maximize the DOP of the transmitted signal ensures that the link remains in a compensated state.[7]

In the two-dimensional Stokes space representation of Fig. 5 (which is a cross section of Stokes space in the plane formed by $\vec{\tau}_{link}$ and $\vec{\tau}_c$), the polarization controller shown in Fig. 4 is capable of rotating $\vec{\tau}_c$ about a circle in the two-dimensional Stokes space. The goal of fixed-delay compensation is to use the polarization controller to adjust the angle between $\vec{\tau}_{link}$ and $\vec{\tau}_c$ until their resultant vector sum, $(\vec{\tau}_{link} + \vec{\tau}_c)$, is aligned with the input state of polarization of the transmitter.[8] As such, with the polarization controller in either position A or position C, the effects of PMD are eliminated by confining the signal entirely to a single PSP. Polarization controller position A is the better of the two operating points since it minimizes the resultant DGD $(\vec{\tau}_{link} + \vec{\tau}_c)$. This is beneficial as it reduces the impact of second-order PMD, which can be a problem when the bandwidth of the transmitter exceeds the bandwidth of the link PSPs.

Curves A and B in Fig. 6 illustrate how the bit error rate (BER) at 10 Gb/s associated with worst case launch midway between the PSPs increases with increasing DGD delay for two different receiver powers. The experimental data in Fig. 6 were obtained using an adjustable first-order PMD emulator and a commercial BER test system. It is evident that log(BER) is approximately proportional to the delay, whereas increasing the power at the receiver for a given delay decreases the BER. The effectiveness of both the fixed delay and PSP transmission PMD compensation techniques are also illustrated in Fig. 6 using compensators which we built. In each case a static PMD emulator consisting of the concatenation of a 40.7-km non-zero dispersion-shifted fibre spool and multiple highly birefringent polarization maintaining fibre sections was used to mimic a high-PMD fibre link. The fixed-delay PMD compensator is seen to decrease the BER from 3.40×10^{-6} to 6.01×10^{-11}, while the PSP transmission compensator produced error-free transmission over a 17-hour test period for a previously uncompensated BER of 1.15×10^{-6}. In both cases the PMD compensation successfully reduced the BER to below the acceptable threshold of 10^{-9}.

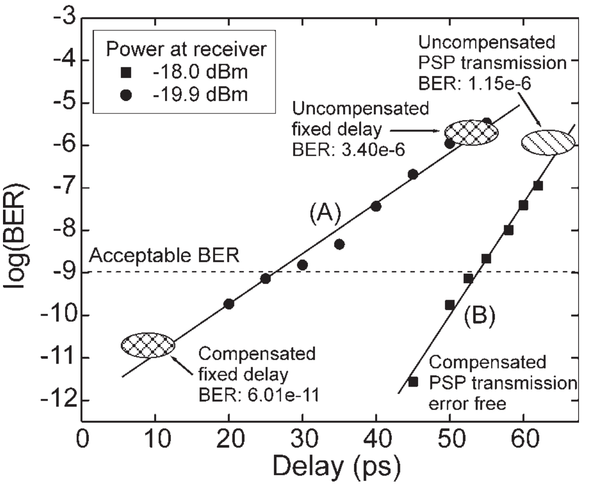

Fig. 6. Experimental results illustrating the effectiveness of PSP transmission and fixed-delay PMD compensation in lowering the PMD-related bit error rate (BER) at 10 Gb/s.

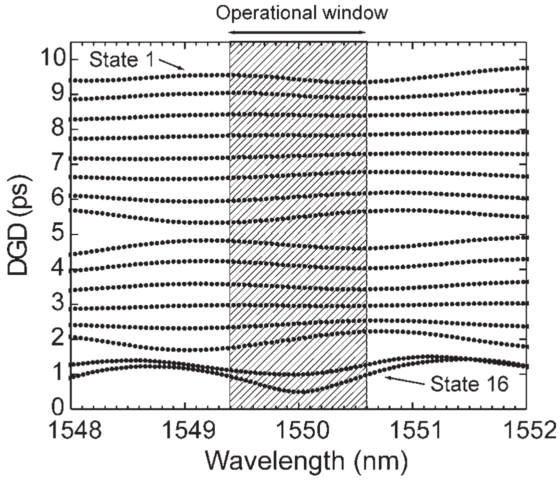

Fig. 7. DGD as a function of wavelength for our variable-delay element in each of its 16 operational states. The device is optimized to operate in the 1.2-nm window at about 1550 nm.

For the third major PMD compensation approach, PMD nulling, a polarization controller followed by a variable-delay element are placed at the output of the fibre link. The setup is thus similar to that of the fixed-delay method, except that the fixed delay is replaced by a variable delay. During PMD nulling, the DGD of the variable-delay element is adjusted to match the DGD of the link, while the polarization controller is used to set the angle between PMD vectors of the link and variable delay to 180° in Stokes space (polarization controller position B in Fig. 5). The PMD of the link and the variable-delay element thus cancel one another.

Over the years, several different types of variable-delay elements for PMD nulling have been demonstrated. These include chirped fibre Bragg gratings,[9,10] motor-driven optical delay lines,[11,12] and multiple twistable polarization maintaining fibre (PMF) sections.[13] The majority of these compensators, however, suffer from being difficult to set accurately, having a slow response, or being very complex due to their many associated degrees of freedom. More recently, polarization switched variable-delay elements have received attention due to their high speed, stability and elegance of operation.[14–16]

Figure 7 shows the results for a polarization switched variable-delay element which we built based on the PMD compensator of Kieckbusch *et al.*[15,16] These authors used a cascade of four birefringent YVO_4 crystals separated by tuneable Faraday rotators, which function as magneto-optic polarization switches. In contrast, we used a cascade of five birefringent PMF sections separated by adjustable half-wave-plate polarization switches. The principle of operation is, however, similar. Our variable-delay element is designed for PMD compensation up to 160 Gb/s and has 16 operational states, which provide a variable delay of between 0.31 ps and 9.69 ps in 0.63 ps steps. With the smallest PMF section chosen as 5% of the bit period (0.31 ps at 160 Gb/s), and delay of each successive element twice that of the preceding element, the residual DGD for a compensated fibre link will always be within 5% of the bit period. This corresponds to a PMD power penalty of less than 0.02 dB. The device has an insertion loss of 2.6 dB and a switching response time of less than 10 ms, making it suitable for rapid PMD compensation in deployed fibre networks.

PMD compensator tracking requirements in deployed fibre

One of the greatest challenges involved in PMD compensation is the need continuously to track the dynamically changing PMD of deployed fibre in real-time. This not only adds to the complexity of the compensation process, but also to the cost due to the reliance on expensive technology such as high speed lithium niobate polarization controllers. PMD compensation is known to be particularly challenging in aerial fibre where the PMD fluctuates on an extremely rapid timescale under the influence of environmental conditions such as wind and temperature variations.[17,18] Buried fibre, on the other hand, is far less exposed to environmental perturbations and the PMD tends to drift slowly under the influence of gradual temperature changes.[19,20] Vibrations and human intervention such as bumping of patchcords can, however, also cause rapid PMD fluctuations in buried fibre, although these generally occur as isolated events.[21,22]

Investigations were performed on two deployed fibre links in the Eastern Cape province in order to investigate the rate of PMD fluctuations under local conditions. This in turn helped estimate the response time tracking requirements that PMD compensators should fulfil under local conditions. The links tested were a 14.9-km aerial loop situated on the outskirts of the city of Port Elizabeth, and a 28.9-km buried loop deployed within the city. In each case a 1550 nm laser with a fixed input state of polarization was transmitted through the fibre and a polarimeter was used to monitor the output SOP. Fluctuating PMD manifests itself as a change in the output SOP, which can be visualized by a point moving about on the Poincaré sphere. The changing SOP is associated with a changing PMD vector ($\vec{\tau}_{link}$ in Fig. 5), which must be continuously tracked in real-time by a PMD compensator in order to guarantee successful PMD compensation.

The inset in Fig. 8 shows the output SOPs on the Poincaré sphere for the aerial fibre as measured over a 20-minute period. The output SOP is seen to be confined to certain regions on the Poincaré sphere, indicating a bias towards certain polarization states. This suggests a periodically repeating environmental disturbance, such as a swaying of the aerial fibre in the breeze. Also shown in Fig. 8 is a histogram of the speed of the output SOP as it moved about the Poincaré sphere over a three-minute period. The average SOP speed was found to be 230 ± 130 deg/s. It should be noted that the data for Fig. 8 were collected on a sunny day with a temperature of about 28°C and a gentle breeze. Greater Poincaré sphere coverage and higher SOP speeds are expected under harsher environmental conditions such as during a storm. In contrast to the rapidly fluctuating SOP observed in aerial fibre, the SOP of the buried fibre link was found to drift slowly at an average speed of 4.86 ± 2.86 deg/h over a 22.4-hour period.

By using an implementation of the Particle Swarm Optimization algorithm[23] to control our fixed-delay PMD compensator, we have been able to demonstrate successful compensation up to average SOP speeds of 38.5 ± 27.6 deg/s in PMD emulators. The response of our PMD compensator is thus more than adequate for tracking the slowly drifting PMD in buried fibre, while not quite sufficient for tracking rapid PMD fluctuations in aerial fibre. An aerial fibre test bed will soon be deployed in the Nelson Mandela Metropolitan University grounds in order to facilitate research into the further development of PMD compensation in aerial fibre.

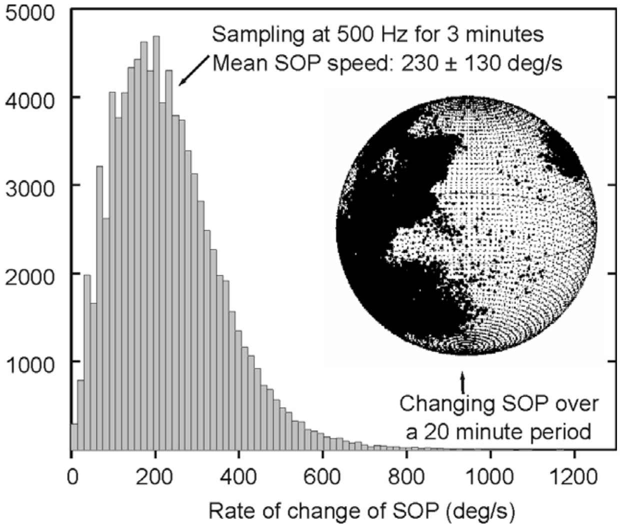

Fig. 8. Histogram of the state of polarization (SOP) speed associated with the rapid PMD fluctuations in a 14.9-km aerial fibre link. The inset shows the changing output SOP over a 20-minute period, as plotted on the Poincaré sphere.

Alternatives to PMD compensation

Given a network with unacceptably high PMD, there are alternatives to PMD compensation. The first is the insertion of costly optical-to-electronic-to-optical converters along the link. Eiselt *et al.* examined the economic feasibility of reducing system reach and using such converters instead of employing PMD compensators.[24,25] Their conclusions suggest that PMD compensation is often economically viable, although the feasibility depends strongly on factors such as the bit rate, the PMD coefficient of the fibre, and the transmission distance. Another possible solution to the PMD problem is to replace entire links with modern low-PMD fibres. Instead of replacing entire links, a polarization optical time domain reflectometer could also be used to identify and replace only those fibre sections which have unacceptably high PMD.[26,27] Additional strategies employed by companies such as France Telecom to mitigate PMD include the use of PMD robust modulation formats, the implementation of forward error correction, the reallocation of non-linear effect penalty margins to PMD in links where non-linear effects were not a problem, and a reduction in the number of channels in order to increase the power of each channel until non-linear effects become a problem.[28] While the best and most cost-effective solution depends on the amount of PMD and the network requirements, PMD compensation is expected to be indispensable at transmission rates of 40 Gb/s and above as a result of the small tolerable PMD margins associated with such high bit rates.

Conclusions

PMD is currently a major obstable in the upgrading of optical-fibre telecommunication networks worldwide. An analysis of countrywide PMD measurement results revealed that the South African network is currently unfit for extensive long-haul applications at 10 Gb/s and beyond. This highlights the need for a suitable intervention strategy if the present network is to be upgraded. The PMD compensation techniques discussed and experimentally illustrated in this paper present themselves as a possible solution to the PMD problem. PMD compensation remains costly and challenging, however, particularly in aerial fibre, where the PMD has been shown to fluctuate extremely rapidly. Ways of alleviating the PMD problem exist. These include replacing entire high-PMD legacy links, using a polarization optical time domain reflectometer to identify and replace high-PMD fibre sections, and the use of PMD robust modulation formats. A detailed analysis of future network requirements and the current network design architecture is required in order to decide on the best and most cost-effective solution to the PMD problem in South Africa.

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