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SERIES G: TRANSMISSION SYSTEMS AND MEDIA,  
DIGITAL SYSTEMS AND NETWORKS

Transmission media and optical systems characteristics –  
Characteristics of optical components and subsystems

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**Characteristics of PMD compensators and PMD  
compensating receivers**

Recommendation ITU-T G.666



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## **Recommendation ITU-T G.666**

### **Characteristics of PMD compensators and PMD compensating receivers**

#### **Summary**

Recommendation ITU-T G.666 contains parameters and definitions for devices providing polarization mode dispersion (PMD) compensation needed for transmission and detection of optical signals in a system exhibiting high levels of PMD which would otherwise cause unacceptable levels of system outage. Single and multichannel line PMD compensators are described, as well as single and multichannel PMD compensating receivers. Information on test configurations and implementation options can be found in informative appendices.

#### **Source**

Recommendation ITU-T G.666 was approved on 29 March 2008 by ITU-T Study Group 15 (2005-2008) under Recommendation ITU-T A.8 procedure.

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## Recommendation ITU-T G.666

### Characteristics of PMD compensators and PMD compensating receivers

#### 1 Scope

This Recommendation contains parameters and definitions for devices providing polarization mode dispersion (PMD) compensation needed for transmission and detection of optical signals in a system exhibiting high levels of PMD. The PMD compensating devices described include both single and multichannel applications. This Recommendation defines requirements and key parameters for first and higher order PMD compensators (PMDCs) and includes dynamic PMD characteristics. This Recommendation distinguishes line PMDCs from PMDC receivers which may comprise electrical as well as optical forms of PMD compensation.

Measurement methods for PMD-related impairments can be found in [ITU-T G.650.2]

#### 2 References

The following ITU-T Recommendations and other references contain provisions which, through reference in this text, constitute provisions of this Recommendation. At the time of publication, the editions indicated were valid. All Recommendations and other references are subject to revision; users of this Recommendation are therefore encouraged to investigate the possibility of applying the most recent edition of the Recommendations and other references listed below. A list of the currently valid ITU-T Recommendations is regularly published. The reference to a document within this Recommendation does not give it, as a stand-alone document, the status of a Recommendation.

- [ITU-T G.650.2] Recommendation ITU-T G.650.2 (2005), *Definitions and test methods for statistical and non-linear related attributes of single-mode fibre and cable.*
- [ITU-T G.652] Recommendation ITU-T G.652 (2005), *Characteristics of a single-mode optical fibre and cable.*
- [ITU-T G.653] Recommendation ITU-T G.653 (2003), *Characteristics of a dispersion-shifted single-mode optical fibre and cable.*
- [ITU-T G.654] Recommendation ITU-T G.654 (2004), *Characteristics of a cut-off shifted single-mode optical fibre and cable.*
- [ITU-T G.655] Recommendation ITU-T G.655 (2003), *Characteristics of a non-zero dispersion-shifted single-mode optical fibre and cable.*
- [ITU-T G.656] Recommendation ITU-T G.656 (2004), *Characteristics of a fibre and cable with non-zero dispersion for wideband optical transport.*
- [ITU-T G.661] Recommendation ITU-T G.661 (1998), *Definition and test methods for the relevant generic parameters of optical amplifier devices and subsystems.*
- [ITU-T G.662] Recommendation ITU-T G.662 (2005), *Generic characteristics of optical amplifier devices and subsystems.*
- [ITU-T G.665] Recommendation ITU-T G.665 (2005), *Generic characteristics of Raman amplifiers and Raman amplified subsystems.*
- [ITU-T G.671] Recommendation ITU-T G.671 (2005), *Transmission characteristics of optical components and subsystems.*
- [ITU-T G.694.1] Recommendation ITU-T G.694.1 (2002), *Spectral grids for WDM applications: DWDM frequency grid.*

[ITU-T G.698.1] Recommendation ITU-T G.698.1 (2006), *Multichannel DWDM applications with single-channel optical interfaces*.

### 3 Terms and definitions

#### 3.1 Terms defined elsewhere

This Recommendation uses the following terms defined elsewhere:

**3.1.1 differential group delay (DGD):** [ITU-T G.650.2], symbol  $\Delta\tau$ .

**3.1.2 polarization dispersion vector (PDV):** [ITU-T G.650.2], symbol  $\vec{\Omega}$ .

NOTE – In a former version of this Recommendation, PDV was called "First order DGD vector". The renaming is due to an alignment of terms with respect to [ITU-T G.650.2].

**3.1.3 principle state of polarization vector:** [ITU-T G.650.2], symbol  $\vec{p}$ .

**3.1.4 ripple:** [ITU-T G.671].

**3.1.5 spectral excursion:** [ITU-T G.698.1].

**3.1.6 Stokes vector:** [ITU-T G.650.2], Symbol  $\vec{s}$ .

#### 3.2 Terms defined in this Recommendation

This Recommendation defines the following terms:

**3.2.1 DGD rate of change:** The DGD rate of change is defined as the absolute value of the derivative of the DGD with respect to time, i.e.,  $\left| \frac{\partial \Delta\tau}{\partial t} \right|$ , and is measured in ps/ms.

**3.2.2 OSNR penalty due to DGD:** An optical signal that has been subject to a DGD requires a larger OSNR at the receiver to achieve  $BER = 10^{-12}$  than an optical signal which has not been affected by DGD (i.e.,  $\Delta\tau = 0$ ), assuming the same receiver input power in both cases. This OSNR difference is called the OSNR penalty due to DGD. In this case no SOPMD is considered.

NOTE – For applications where FEC bytes are required to be transmitted, the BER of  $10^{-12}$  is required to be met only after the error correction (if used) has been applied. The BER at the input of the FEC decoder for these cases can therefore be significantly higher than  $10^{-12}$ .

**3.2.3 polarization rotation speed (PRS):** The polarization rotation speed is the absolute value of the temporal change of the Stokes vector  $\vec{s}$ , i.e.,  $PRS = \left| \frac{\partial \vec{s}}{\partial t} \right|$ , and is measured in rad/ms.

**3.2.4 PMDC receiver sensitivity:** The value of mean received power at point MPI-R to achieve the specified BER. This must be met across all states of input polarization with a worst-case transmitter, but does not have to be met with degradations of the optical path other than the PMD.

**3.2.5 PSP rate of change:** The PSP rate of change is defined as the derivative of the principle state of polarization vector  $\vec{p}$  in Stokes space with respect to time, i.e.,  $\left| \frac{\partial \vec{p}}{\partial t} \right|$ , and is measured in rad/ms.

**3.2.6 second-order PMD (SOPMD):** Second-order PMD is defined by  $SOPMD = \vec{\Omega}_\omega = \Delta\tau_\omega \vec{p} + \Delta\tau \vec{p}_\omega$ . This is the derivative of the PDV (first-order DGD vector) with respect to the optical frequency  $\omega$ . The SOPMD consists of two terms, namely  $\Delta\tau_\omega \vec{p}$  and  $\Delta\tau \vec{p}_\omega$ . The first term,  $\Delta\tau_\omega \vec{p}$ , represents the polarization-dependent chromatic dispersion term (PCD),



while  $\Delta\tau \vec{p}_\omega$  is the so-called depolarization term (DEPOL) which describes the PSP unit vector rotation with respect to frequency (at the centre frequency of the signal). The corresponding magnitudes of these quantities are given as follows: Magnitude of the SOPMD =  $|\vec{\Omega}_\omega|$ , magnitude of the depolarization =  $|\Delta\tau \vec{p}_\omega|$ , magnitude of the PCD =  $|\Delta\tau_\omega|$ .

#### 4 Abbreviations and acronyms

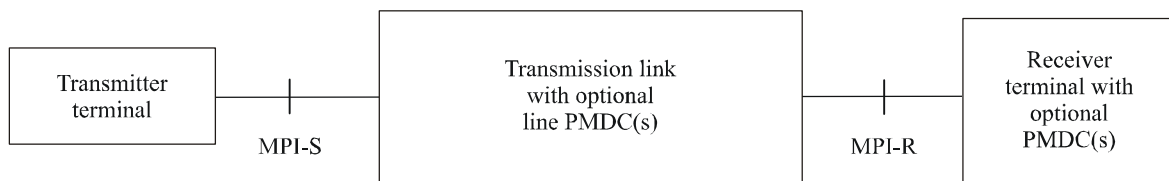
This Recommendation uses the following abbreviations and acronyms:

BER	Bit Error Ratio
DEMUX	Demultiplexer
DEPOL	Depolarization term
DGD	Differential Group Delay
LPMDC	Line Polarization Mode Dispersion Compensator
M-LPMDC	Multichannel Line Polarization Mode Dispersion Compensator
M-PMDC-Rx	Multichannel Polarization Mode Dispersion Compensating Receiver
MPI	Main Path Interface
MUX	Multiplexer
NRZ	Non-Return to Zero
OA	Optical Amplifier
O-E-O	Optical-Electrical-Optical (conversion)
OSNR	Optical Signal-to-Noise Ratio
PCD	Polarization-dependent Chromatic Dispersion
PDL	Polarization Dependent Loss
PDV	Polarization Dispersion Vector
PMD	Polarization Mode Dispersion
PMDC	Polarization Mode Dispersion Compensator
PMDC-Rx	Polarization Mode Dispersion Compensating Receiver
PRBS	Pseudo-Random Binary Sequence
PRS	Polarization Rotation Speed
PSP	Principle State of Polarization
RZ	Return to Zero
S-LPMDC	Single-Channel Line Polarization Mode Dispersion Compensator
S-PMDC-Rx	Single-Channel Polarization Mode Dispersion Compensating Receiver
SOP	State of Polarization
SOPMD	Second Order Polarization Mode Dispersion
WDM	Wavelength Division Multiplexing

## 5 Reference configurations

PMDCs are intended to be used in optical transmission systems in order to reduce PMD-induced signal degradations. Therefore, characteristics of PMDCs must be considered, at least in part, in conjunction with a whole transmission system.

A generic configuration of a transmission system with PMDC(s) is shown in Figure 5-1. It consists of a transmitter terminal, a receiver terminal and a transmission link in between with optional line PMDC(s). A single-channel system contains a single-channel transmitter and receiver terminal while a multichannel transmitter and receiver terminal is used in a multichannel system. The receiver terminal can also contain optional PMDC functionalities and is called a "PMDC receiver" in this case. In the following clauses, optical line PMDCs (LPMDC) are distinguished from PMDC receivers. A black box approach is applied for the PMDCs and PMDC receivers. Monitoring and control (if present) is included in the black box.



G.666\_F5-1

**Figure 5-1 – Generic configuration of a transmission system with PMDCs**

### 5.1 Line PMDCs

Line PMDCs have an optical input and an optical output port and no O-E-O conversion is performed inside a line PMDC. A single-channel line PMDC (S-LPMDC) can handle a single-channel optical signal, while a multichannel line PMDC (M-LPMDC) is constructed for a multichannel optical signal. Both types are illustrated schematically in Figures 5-2 and 5-3, respectively.



G.666\_F5-2

**Figure 5-2 – Reference configuration of a single-channel line PMDC (S-LPMDC)**



G.666\_F5-3

**Figure 5-3 – Reference configuration of a multichannel line PMDC (M-LPMDC)**

### 5.2 PMDC receivers

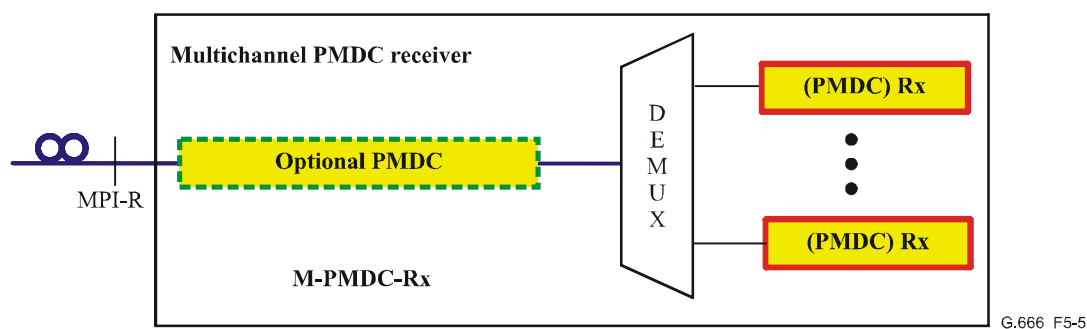
In the case of PMDC receivers (PMDC-Rx), the PMDC functionality is embedded in the receiver terminal. There are a number of options regarding how to realize PMDC receivers. Single-channel PMDC receivers are distinguished from multichannel PMDC receivers.

A schematic diagram of a single-channel PMDC receiver (S-PMDC-Rx) is shown in Figure 5-4. A single-channel optical signal enters the receiver terminal at the reference point MPI-R. There the PMDC functionality is performed and the signal is then detected. Implementation details on single-channel PMDC receivers (e.g., optical vs electrical) can be found in Appendix II.



**Figure 5-4 – Reference configuration of a single-channel PMDC receiver**

A multichannel PMDC receiver is presented schematically in Figure 5-5. A multichannel optical signal enters the receiver terminal at the reference point MPI-R. There, it either passes a PMDC before entering a demultiplexer (DEMUX) and the receivers (Rx) for the individual optical channels, or it passes directly through the demultiplexer where all of the receivers are PMDC-Rx. Further implementation details can be found in clause II.2.



**Figure 5-5 – Reference configuration of a multichannel PMDC receiver (M-PMDC-Rx)**

## 6 Parameters of PMDCs

In this clause, parameters for PMDCs are presented. Some parameters apply to all PMDC types and they are summarized in Table 6-1. In the following Tables 6-2 to 6-5, additional parameters can be found which apply to the individual PMDC types.

**Table 6-1 – Common parameters which apply to all PMDC types**

Parameters	Reference point	Unit	Examples (for illustration of particular applications only)
<b>Fibre type</b>			
Line fibre type	MPI-S $\rightarrow$ R <sub>S</sub> or MPI-S $\rightarrow$ R <sub>M</sub> or MPI-S $\rightarrow$ MPI-R	–	G.652.D, G.653, G.654, G.655, G.656
<b>Parameters related to optical power</b>			
Minimum total input power	R <sub>S</sub> or R <sub>M</sub> or MPI-R	dBm	
Maximum total input power	R <sub>S</sub> or R <sub>M</sub> or MPI-R	dBm	
Maximum reflectance at the input port	R <sub>S</sub> or R <sub>M</sub> or MPI-R	dB	
Polarization dependent reflectance at the input port	R <sub>S</sub> or R <sub>M</sub> or MPI-R	dB	

**Table 6-1 – Common parameters which apply to all PMDC types**

Parameters	Reference point	Unit	Examples (for illustration of particular applications only)
<b>Optical signal characteristics</b>			
Minimum bit rate	R <sub>S</sub> or R <sub>M</sub> or MPI-R	Gbit/s	
Maximum bit rate	R <sub>S</sub> or R <sub>M</sub> or MPI-R	Gbit/s	
Modulation format (or "signal format")	R <sub>S</sub> or R <sub>M</sub> or MPI-R	–	"Any format", "only NRZ", "NRZ and RZ"
<b>Polarization-independent parameters of the preceding optical path</b>			
Minimum amount of accumulated chromatic dispersion	MPI-S → R <sub>S</sub> or MPI-S → R <sub>M</sub> or MPI-S → MPI-R	ps/nm	
Maximum amount of accumulated chromatic dispersion	MPI-S → R <sub>S</sub> or MPI-S → R <sub>M</sub> or MPI-S → MPI-R	ps/nm	
<b>Polarization parameters at the input port</b>			
Maximum average input DGD	R <sub>S</sub> or R <sub>M</sub> or MPI-R	ps	
Maximum instantaneous input DGD	R <sub>S</sub> or R <sub>M</sub> or MPI-R	ps	
Maximum polarization rotation speed	R <sub>S</sub> or R <sub>M</sub> or MPI-R	rad/ms	
Maximum DGD rate of change	R <sub>S</sub> or R <sub>M</sub> or MPI-R	ps/ms	
PSP rate of change	R <sub>S</sub> or R <sub>M</sub> or MPI-R	rad/ms	
Maximum magnitude of the PCD	R <sub>S</sub> or R <sub>M</sub> or MPI-R	ps <sup>2</sup>	
Maximum magnitude of the depolarization	R <sub>S</sub> or R <sub>M</sub> or MPI-R	ps <sup>2</sup>	

**Table 6-2 – Parameters which apply to a single-channel line PMDC (S-LPMDC)**

Parameters	Reference point	Unit	Examples (for illustration of particular applications only)
<b>General single-channel optical parameters</b>			
Nominal central optical frequency	R <sub>S</sub>	THz	
Maximum spectral excursion	R <sub>S</sub>	GHz	
<b>Parameters related to optical power</b>			
Minimum insertion loss (incl. optional OA unit)	R <sub>S</sub> → S <sub>S</sub>	dB	
Maximum insertion loss (incl. optional OA unit)	R <sub>S</sub> → S <sub>S</sub>	dB	
Maximum insertion loss deviation	R <sub>S</sub> → S <sub>S</sub>	dB	
Ripple	R <sub>S</sub> → S <sub>S</sub>	dB	
Noise figure (if an OA unit is used)	R <sub>S</sub> → S <sub>S</sub>	dB	
Polarization dependent loss (PDL)	R <sub>S</sub> → S <sub>S</sub>	dB	

**Table 6-2 – Parameters which apply to a single-channel line PMDC (S-LPMDC)**

Parameters	Reference point	Unit	Examples (for illustration of particular applications only)
<b>Polarization parameters related to the output port (Note 1)</b>			
Maximum average output DGD (Note 2)	$S_S$	ps	
Maximum instantaneous output DGD (Note 2)	$S_S$	ps	
Maximum magnitude of the SOPMD (Note 2)	$S_S$	ps <sup>2</sup>	
NOTE 1 – In order to ensure transverse compatibility between line PMDCs and optical receivers, additional parameters may be required.			
NOTE 2 – These parameters must be met for input PMD within the limits indicated in the "polarization parameters at the input port" section in Table 6-1.			

**Table 6-3 – Parameters which apply to a multichannel line PMDC (M-LPMDC)**

Parameters	Reference point	Unit	Examples (for illustration of particular applications only)
<b>General multichannel optical parameters</b>			
Maximum number of channels	$R_M$	–	
Nominal channel central frequencies	$R_M$	THz	191.9 + 0.2 m, m = 0 to 19
Channel spacing	$R_M$	GHz	200
Maximum spectral excursion	$R_M$	GHz	
<b>Parameters related to optical power</b>			
Minimum channel input power	$R_M$	dBm	
Maximum channel input power	$R_M$	dBm	
Minimum channel insertion loss (incl. optional OA unit)	$R_M \rightarrow S_M$	dB	
Maximum channel insertion loss (incl. optional OA unit)	$R_M \rightarrow S_M$	dB	
Maximum channel insertion loss deviation	$R_M \rightarrow S_M$	dB	
Ripple	$R_M \rightarrow S_M$	dB	
Noise figure (if an OA unit is used)	$R_M \rightarrow S_M$	dB	
Polarization dependent loss (PDL)	$R_M \rightarrow S_M$	dB	
<b>Polarization parameters applied to each channel related to the output port (Note 1)</b>			
Maximum average output DGD (Note 2)	$S_M$	ps	
Maximum instantaneous output DGD (Note 2)	$S_M$	ps	
Maximum magnitude of SOPMD (Note 2)	$S_M$	ps <sup>2</sup>	
NOTE 1 – In order to ensure transverse compatibility between line PMDCs and optical receivers, additional parameters may be required.			
NOTE 2 – These parameters must be met for input PMD within the limits indicated in the "polarization parameters at the input port" section in Table 6-1.			

**Table 6-4 – Parameters which apply to a single-channel PMDC receiver (S-PMDC-Rx)**

Parameters	Unit	Examples (for illustration of particular applications only)
<b>General single-channel optical parameters</b>		
Nominal central optical frequency	THz	
Maximum spectral excursion	GHz	
<b>Single-channel transmission system parameters</b>		
Maximum OSNR penalty due to DGD	dB	
Minimum PMDC receiver sensitivity	dBm	

**Table 6-5 – Parameters which apply to a multichannel PMDC receiver (M-PMDC-Rx)**

Parameters	Unit	Examples (for illustration of particular applications only)
<b>General multichannel optical parameters</b>		
Maximum number of channels	–	
Nominal channel central frequencies	THz	191.9 + 0.2 m, m = 0 to 19
Channel spacing	GHz	200
Maximum spectral excursion	GHz	
<b>Parameters related to optical power</b>		
Minimum channel input power	dBm	
Maximum channel input power	dBm	
<b>Multichannel transmission system parameters applied to each channel</b>		
Maximum OSNR penalty due to DGD	dB	
Minimum PMDC receiver sensitivity	dBm	

# Appendix I

## Measurements of parameters of PMDCs

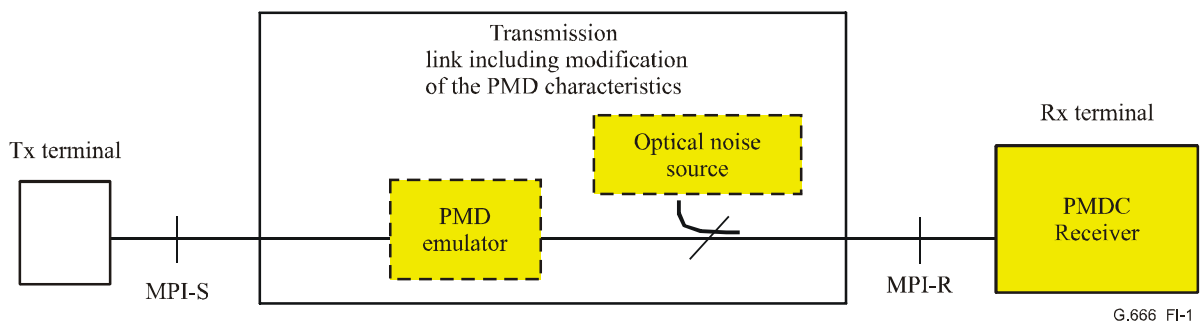
(This appendix does not form an integral part of this Recommendation)

This appendix covers approaches to the measurement of the parameters of PMDCs. A test configuration should contain a transmission link with PMD tuning capabilities (thus including the transmission fibre and a PMD emulator) followed by the PMDC and a test instrumentation to measure the PMDC characteristics.

There are two different categories of PMDCs, namely PMDC receivers and line PMDCs. PMDC receivers include S-PMDC-Rxs and M-PMDC-Rxs. Line PMDCs include S-LPMDCs and M-LPMDCs. A generic approach to measurement of parameters for these PMDCs is shown below.

### I.1 Measurement of parameters for PMDC receivers

A generic test configuration for measuring parameters of PMDC receivers is shown in Figure I.1. For reasons of simplicity, a single-channel transmitter and receiver terminal is assumed. The single-channel optical signal passes a transmission link which contains an adjustable PMD emulator and an optical noise source. Additional optical components (not shown here) are used to ensure constant optical input power at the reference point MPI-R in front of the PMDC receiver.



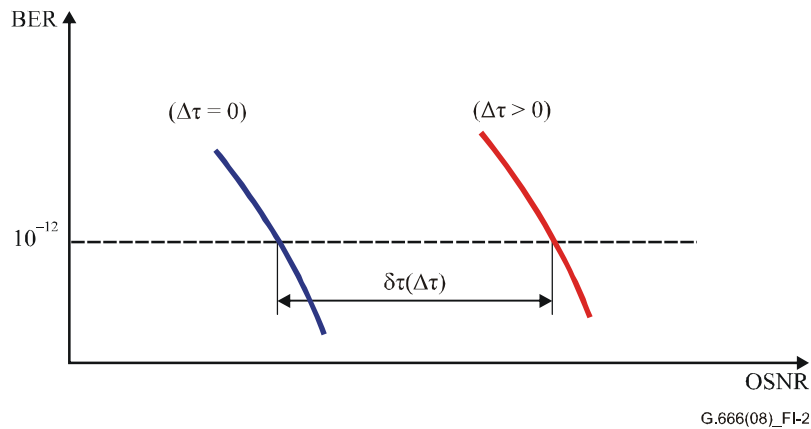
**Figure I.1 – Generic configuration for measuring parameters of PMDC receivers**

In order to measure the OSNR penalty with respect to DGD, a first order PMD emulator is adjusted to DGD values in the DGD interval  $0 \leq \Delta\tau \leq \Delta\tau_{\max}$ . Here,  $\Delta\tau$  denotes the differential group delay (DGD), and  $\Delta\tau_{\max}$  is the limit of the first order PMD that the receiver is required to tolerate.

NOTE – Most commercially available PMD emulators require a fixed input polarization of  $45^\circ$  with respect to their input PSP for optimum operation. Thus the state of polarization at the input of the PMD emulator has to be controlled. Two approaches for this are:

- 1) A fixed and stable  $45^\circ$  state of polarization is ensured at the input of the PMD emulator. In this case, the distance between the Tx terminal and the PMD emulator is usually very short, thus avoiding unwanted polarization fluctuations due to a long length of fibre.
- 2) If a long fibre section between the Tx terminal and the input of the PMD emulator is unavoidable then the state of polarization at the input of the PMD emulator is usually random. In order to cope with this problem, a polarization controller which continuously rotates the polarization is inserted in front of the PMD emulator. As a consequence, the influence of the random polarization is averaged. The rotation speed of this polarization controller has to be adapted carefully to the input requirements of the PMDC receiver.

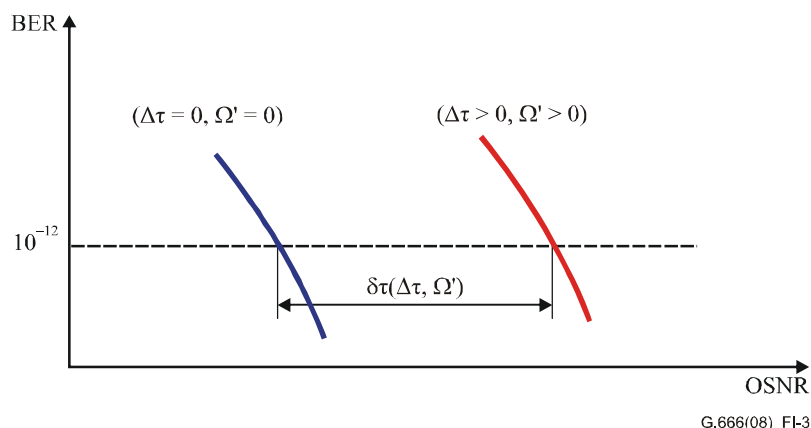
The BER is measured versus OSNR (while maintaining a constant optical input power  $P_{in}$  at MPI-R). The BER curve at a value  $\Delta\tau > 0$  may be shifted with respect to the BER curve at zero DGD (i.e., at  $\Delta\tau = 0$ ). A schematic view of this behaviour is shown in Figure I.2. The PMD-induced penalty at  $BER = 10^{-12}$  between a polarization state with DGD  $\Delta\tau > 0$  and the zero DGD state ( $\Delta\tau = 0$ ) is denoted as  $\delta\tau$ .



**Figure I.2 – Schematic view of the BER versus OSNR for zero and non-zero DGD  $\Delta\tau$**

The measurement set-up shown in Figure I.1 can also be used to measure the OSNR penalty with respect to both the DGD and SOPMD. In this case, a second order PMD emulator is used. This PMD emulator can be adjusted to any pair of values  $(\Delta\tau, \Omega')$  in the DGD interval  $0 \leq \Delta\tau \leq \Delta\tau_{max}$  and the SOPMD interval  $0 \leq \Omega' \leq \Omega'_{max}$ . Here,  $\Delta\tau$  denotes the differential group delay (DGD),  $\Omega' = |\vec{\Omega}'_{\omega}|$  denotes the amount of SOPMD whereby  $\vec{\Omega}'_{\omega}$  is the derivative of the PDV (first order DGD vector)  $\vec{\Omega}(\omega)$  with respect to  $\omega$ , and  $\Delta\tau_{max}$  and  $\Omega'_{max}$  are the limits of the DGD and SOPMD that the receiver is required to tolerate.

The same principle is applied as shown in Figure I.2. However, the BER curves are measured as a function of two PMD parameters, namely DGD and SOPMD. A schematic view of this behaviour is shown in Figure I.3.



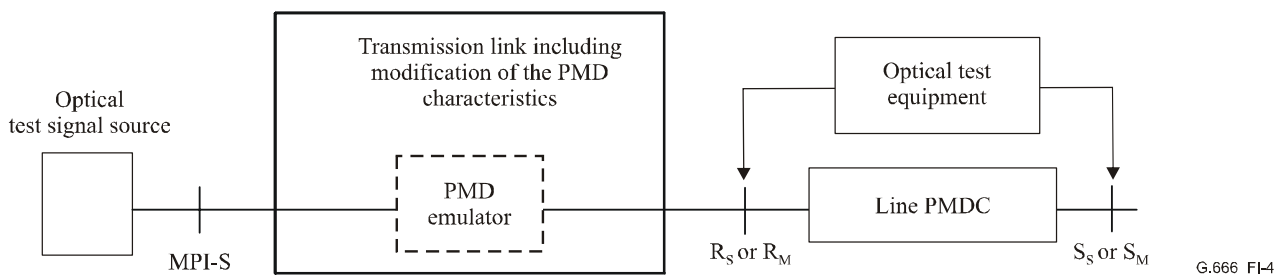
**Figure I.3 – Schematic view of the BER versus OSNR for zero and non-zero DGD  $\Delta\tau$  and SOPMD  $\Omega'$**



The BER is measured versus OSNR (rather than versus optical input power) at the reference point MPI-R for the following reason: PMD usually becomes an issue for very high data rates (10 Gbit/s and above) and long optically transparent link lengths. In other words, PMD usually becomes an issue in multi-span transmission systems which (per definition) include optical amplifiers (OAs). OSNR is a fundamental limitation of such multi-span systems due to noise accumulation of the OAs. The minimum OSNR that the system can tolerate is given by the minimum OSNR in the absence of any PMD-induced distortions plus the additional penalty  $\delta\tau (\Delta\tau, \Omega')$  due to the impact of DGD and SOPMD. The additional penalty  $\delta\tau (\Delta\tau, \Omega')$  in dB is represented by the amount that the OSNR must be improved in the presence of PMD to maintain the required BER.

## I.2 Measurement of parameters for line PMDCs

A generic test configuration for measuring parameters of line PMDCs is shown in Figure I.4.



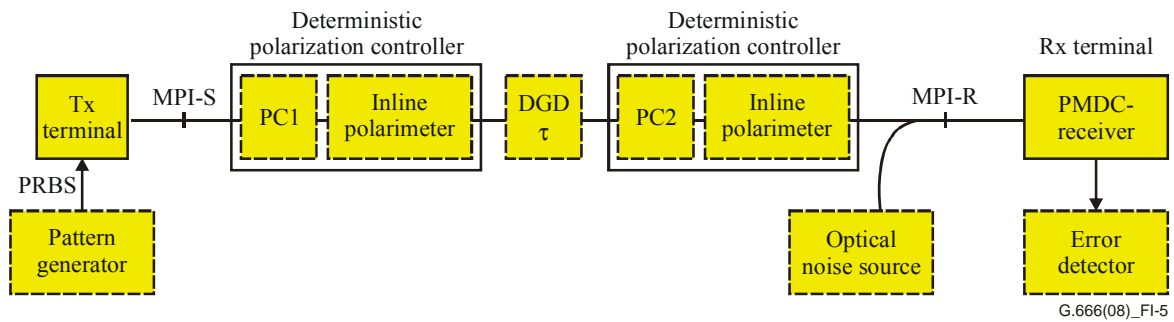
**Figure I.4 – Generic configuration for measuring parameters of line PMDCs**

In the case of line PMDCs, only optical parameters are measured at the input and the output port of the Line PMDC. The BER is not measured.

## I.3 First order dynamic PMD emulator implementation

Figure I.5 shows one possible realization of a test set-up suitable for the evaluation of a PMDC receiver with respect to dynamic DGD tolerance. Higher order effects cannot be measured with this set-up.

The basic approach is to provide a PMD emulator (consisting of two deterministic polarization controllers with a DGD element in between) with completely deterministic settings. The deterministic behaviour includes dynamic changes of the state of polarization (SOP) with a well-defined polarization rotation speed (PRS, measured in rad/ms). With random polarization scrambling, the maximum PRS can be selected, but it will only rarely be present. The same is true for the polarization at the input of the DGD element, which sets the signal distortion. With deterministic scrambling it is possible to test the PMDC receiver under worst case conditions and therefore to reduce measurement time and increase reproducibility of the results dramatically.



**Figure I.5 – Possible test set-up for characterizing the first order PMD tolerance of a PMDC receiver**

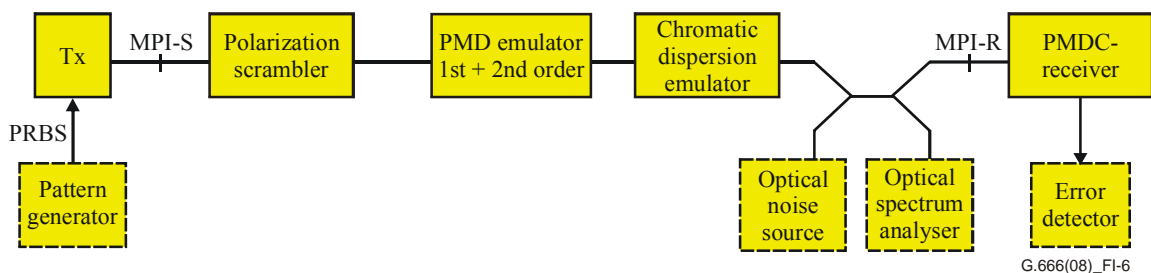
In the case that the input polarization to the dynamic PMD emulator is stable over the measurement time (normal scenario), the inline polarimeters are only used during the calibration process of the PMD emulator. For applications where this is not the case, the inline polarimeter at PC1 can be used to detect changes of the input polarization and a correction via PC1 can be implemented. After calibration, the polarization controllers can be used to set the SOP, the PRS and the PSP rate of change in a deterministic way. The first polarization controller (PC1) is used to adjust the SOP at the input of the DGD element and therefore to set the PRS and worst case polarization (i.e., continuously rotating the SOP such that the power splitting between the fast and slow axis of the DGD element changes continuously from 0 to 0.5 to 1 to 0.5, and so on). The second polarization controller (PC2) is used to rotate the PSP of the PMD emulator with a predefined PSP rate of change. This results in a relative change of the emulator PSP to the PSP of any DGD element which is possibly used inside the PMDC-receiver. A calibration procedure can be used to find the appropriate settings of PC2 corresponding to the desired values of the PSP rate of change. For testing the PMDC receiver, both PCs can be operated simultaneously. The PRS at MPI-R will be a result of the PRS induced by PC1 and the PSP rate of change induced by PC2.

#### I.4 First and second order PMD emulator implementation

This clause shows an implementation example for the evaluation of a PMDC receiver with respect to static PMD tolerance for first order and second order PMD. Unlike the arrangement described in clause I.3, this implementation is not able to apply or track fast PMD changes.

##### I.4.1 Measurement procedure

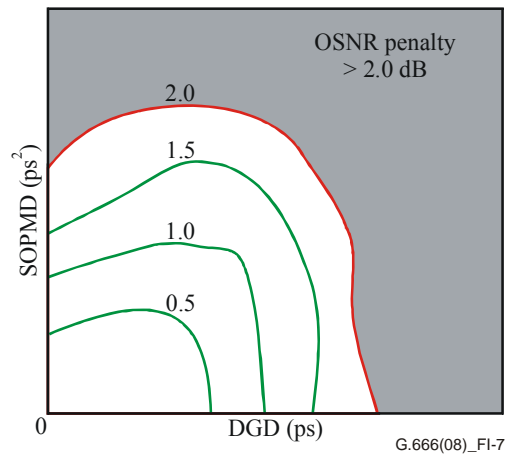
The measurement set-up is shown in Figure I.6. Between the transmitter (Tx) and PMDC receiver are inserted a polarization scrambler, PMD emulator and chromatic dispersion emulator. This enables a known magnitude of first and second order PMD to be applied together with a known amount of chromatic dispersion. An optical noise source is also included to provide noise loading at the input of the PMDC receiver.



**Figure I.6 – Measurement set-up for determination of first and second order PMD tolerance**

The PMD emulator is set to different combinations of first and second order PMD and the BER and OSNR values are measured with an optical spectrum analyser (OSA) and bit error ratio tester (BERT), respectively. As a result, a certain OSNR penalty with respect to the undistorted case is measured as illustrated in Figure I.7. In this figure, the X and Y axes are the magnitude of the first order (DGD) and second order PMD (SOPMD) respectively, and the lines are contours of constant OSNR penalty (in dB). This plot is also called a two-dimensional distortion plane.

During the measurement process, all points in this plane need to be measured or, more practically, obtained by interpolation from measurements in the neighbourhood. For the example shown in Figure I.7, the allowable OSNR penalty is set at 2.0 dB maximum and the region where this penalty is exceeded is shown shaded.

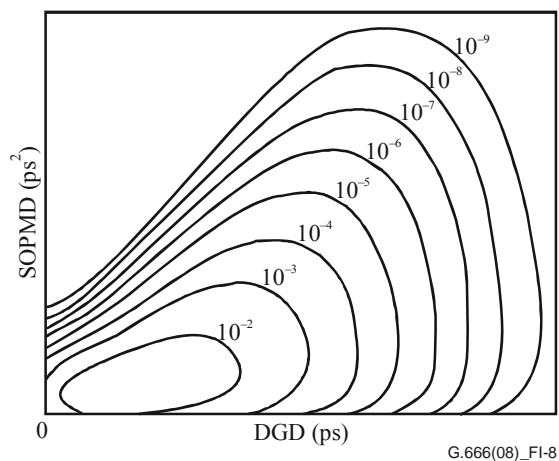


**Figure I.7 – Example lines of constant OSNR penalty for first and second order PMD (DGD and SOPMD)**

The shape of this two-dimensional distortion plane, however, also depends on the value of the chromatic dispersion present in the link, so this whole measurement procedure must be repeated for various levels of chromatic dispersion, including the limiting residual dispersion values of the target application.

Measurement examples of this two-dimensional distortion plane have been published [b-Klekamp] for 43 Gbit/s NRZ and RZ format without additional chromatic dispersion emulation.

Figure I.8 shows the joint probability density function for first and second order PMD. The axes are the same as for Figure I.7, but the lines are now drawn through points of equal probability of occurrence. This is the joint probability density function (pdf  $p_j$ ) for a particular value of mean DGD.



**Figure I.8 – Joint probability density function for first and second order PMD (DGD and SOPMD)**

#### I.4.2 PMD vector in Stokes space

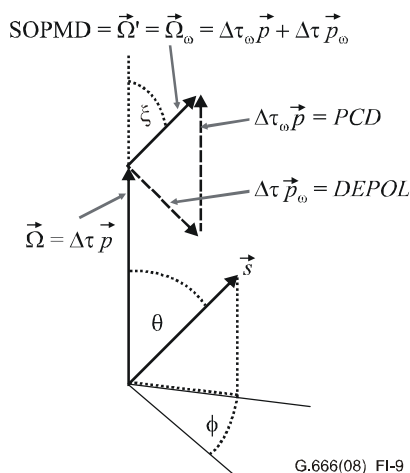
Generally, PMD can be described by a Taylor series according to:

$$\vec{\Omega}(\omega_0 + \Delta\omega) = \vec{\Omega}(\omega_0) + \vec{\Omega}' \cdot \Delta\omega + \dots \quad (\text{I.1})$$

Focusing on the first and second order contribution, the PMD is determined by the PDV (first order DGD vector)  $\vec{\Omega}(\omega_0)$  with  $\omega_0$  as the signal centre frequency and the second order PMD vector:

$$\text{SOPMD} = \vec{\Omega}' = \vec{\Omega}'_{\omega} = \Delta\tau_{\omega} \vec{p} + \Delta\tau \vec{p}_{\omega} \quad (\text{I.2})$$

Figure I.9 depicts possible orientations of different PMD contributions in Stokes space together with the signal state of polarization  $\vec{s}$ .



**Figure I.9 – PMD vectors  $\Omega$  (first order) and  $\Omega'$  (second order), including PCD, DEPOL and signal state of polarization (SOP)  $\vec{s}$**

### I.4.3 Calculation of outage probability (OP) versus first and second order PMD

Generally, the distortion of a signal degraded by first and second order PMD and the corresponding outage probability can be quantified by numerical integration over a set of five parameters as reported in [b-Bülow] and [b-Foschini]:

$$OP = \iiint\limits_{OSNR\ penalty > limit} p_j^* d|\vec{\Omega}|d|\vec{\Omega}'|d\theta d\phi d\xi \quad (I.3)$$

The measurement and calculation of the OP can be accelerated by a reduction of the PMD emulation to only 2 parameters, by:

- Scrambling the state of polarization (SOP) of the signal during BER acquisition to eliminate the need to set the two angles  $\theta$  and  $\phi$  describing the orientation relative to the PSP vector  $\vec{p}$ .
- Setting the mutual orientation ( $\xi$ ) between the first and second order PMD vectors  $\Omega$  and  $\Omega_\omega$  to 90 degrees in the PMD emulator. This corresponds to a worst-case distortion of the second order PMD (maximum depolarization and no PMD-induced chromatic dispersion).

The reduction by three distortion parameters leads to the two dimensional pdf  $p_j$  by the integration of  $p_j^*$  over the angles  $\theta$ ,  $\phi$  and  $\xi$ . Thus, the outage probability formula (equation I.3) can be simplified and expressed by (equation I.4):

$$OP = \iint\limits_{OSNR\ penalty > limit} p_j d|\vec{\Omega}|d|\vec{\Omega}'| \equiv \iint\limits_{OSNR\ penalty > limit} p_j dDGD d|SOPMD| \quad (I.4)$$

Finally, the outage probability is the numerical integration of the pdf  $p_j$  over the area with the OSNR penalty exceeding the limit (shaded area in Figure I.7). The two integration parameters are the DGD in ps (magnitude of the first order PMD vector  $\Omega$ ) and SOPMD, the second order PMD in ps/GHz or ps<sup>2</sup> (magnitude of the second order PMD vector  $\Omega'$ ), respectively.

Figure I.10 shows an example of the calculated OP versus PMD derived from measurement of the two dimensional distortion plane using a 43 Gbit/s NRZ transmitter and receiver, with and without a receiver based PMDC. The X axis of Figure I.10 (labelled PMD) is equal to the mean DGD value which indicates the level of both first and second order PMD. An OSNR penalty of 2 dB has been applied as the OSNR penalty limit. If the outage probability that is considered acceptable is  $10^{-5}$ , then the maximum input PMD of the receiver (PMD tolerance) at 2 dB of OSNR penalty are 2.7 ps and 4.5 ps for the cases without and with PMDC, respectively.

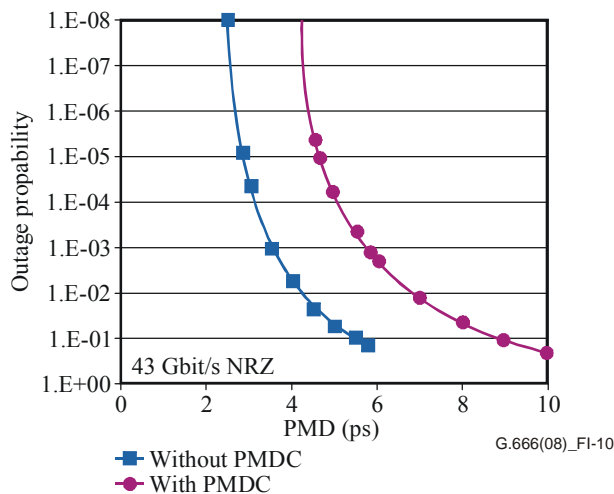


Figure I.10 – Outage probability versus PMD at 43 Gbit/s NRZ, with and without PMDC

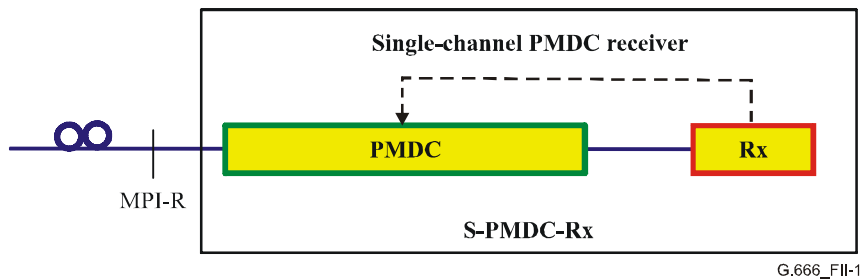
## Appendix II

### Single-channel and multichannel PMDC receiver implementation

(This appendix does not form an integral part of this Recommendation)

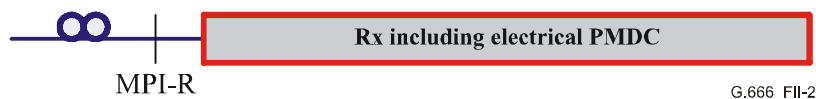
#### II.1 Single-channel PMDC receiver implementation

Single-channel PMDC receivers (as shown generically in Figure 5-4) can be realized by different implementation schemes. One option is a single-channel line PMDC (S-LPMD) as presented in Figure II.1, together with a conventional receiver. The optical signal behind the reference point MPI-R passes through an optical PMDC before entering the receiver. The optional feedback loop shown with a dashed line in Figure II.1 allows the PMDC to operate in an optimized regime.



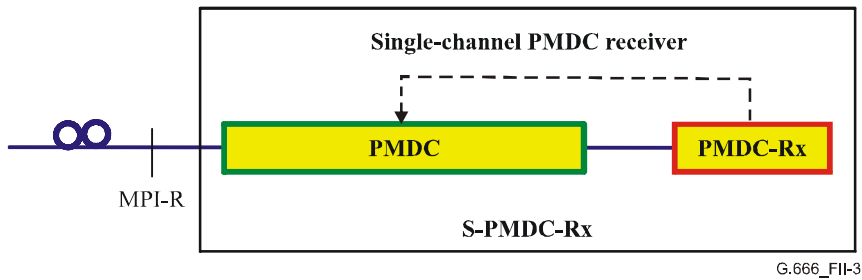
**Figure II.1 – Implementation option A of a single-channel PMDC receiver (S-PMDC-Rx)**

An alternative implementation is the use of a receiver including electrical PMDC, as indicated in Figure II.2. No additional optical device is used for the purpose of PMD compensation. Instead, the PMDC function is achieved inside the receiver by electrical means.



**Figure II.2 – Implementation option B of a single-channel PMDC receiver (S-PMDC-Rx)**

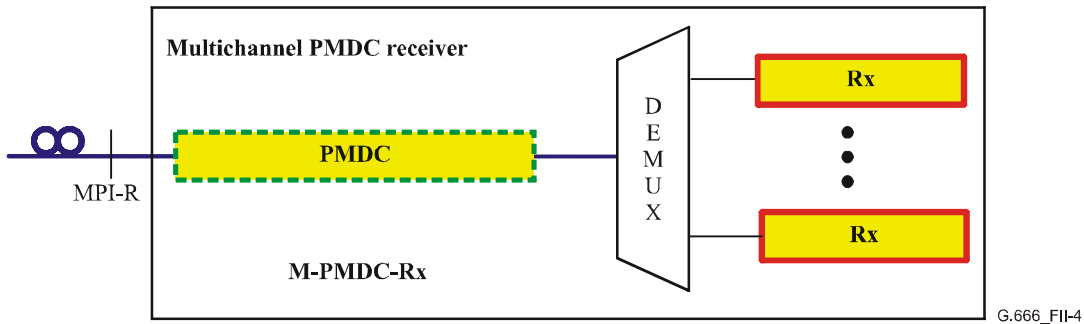
A combination of the two above implementations is also possible as shown in Figure II.3.



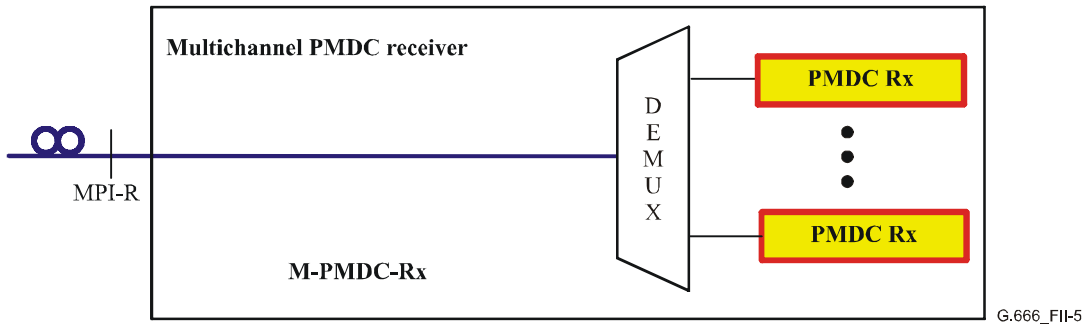
**Figure II.3 – Implementation option C of a single-channel PMDC receiver (S-PMDC-Rx)**

## II.2 Multichannel PMDC receiver implementation

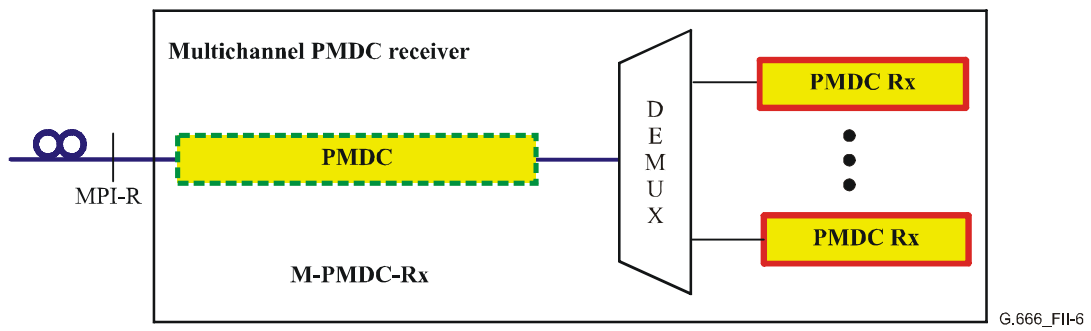
Similarly to clause II.1, there are three implementation options for multichannel PMDC receivers. These are illustrated in Figures II.4-II.6. Option A includes an optical PMDC in front of the demultiplexer with conventional receivers. Option B uses only PMDC receivers. Option C uses a combination of both an optical PMDC in front of the demultiplexer and PMDC receivers.



**Figure II.4 – Implementation option A of a multichannel PMDC receiver (M-PMDC-Rx)**



**Figure II.5 – Implementation option B of a multichannel PMDC receiver (M-PMDC-Rx)**



**Figure II.6 – Implementation option C of a multichannel PMDC receiver (M-PMDC-Rx)**



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