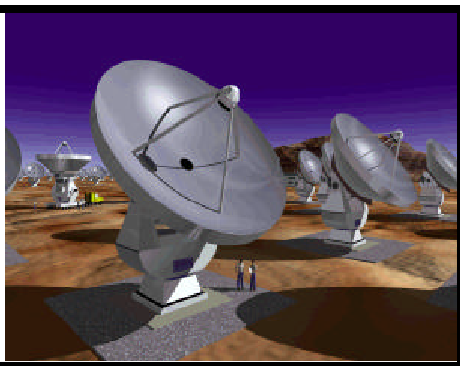

ALMA

Atacama Large Millimeter Array

Overview Document

"ALMA IF Data Transfer Links"

" 18/3/02"

"Roshene McCool"

"IF Data Transfer Links - overview"

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Table of Contents

ALMA Project Design Review
Data Transmission over Fibre Optic Links – A design overview

Introduction

This document describes the optical data transmission system proposed for the ALMA telescope. It details the physical structure of the optic links, the design calculations undertaken to prove the design and a description of the safety issues associated with the optical link design.
The control and monitoring for the system is not covered here.
References are made to good standard texts on this subject. Please refer to these texts for more detailed explanations of the topics described below.

System Description

The ALMA fibre optic transmission system will transfer data from each of the 64 antennas on site to a central correlator. The "baseline" data transfer system (as discussed here) assumes that both the antenna and correlator locations are at the Chajnantor plateau and that the maximum distance between the two will be 25km. The system has to carry 120Gbps from each antenna to the correlator. The 120Gbps is made up of 4 bands at 2 polarisations, each 2GHz wide produced at the antenna. The 2GHz-wide bands are digitised to 3 bits of precision at the Nyquist rate and an additional 8 to 10 bit encoding protocol added for transmission[1] over fibre.
The 120Gbps per antenna will be split into 12, 10 Gbps channels. Dense Wavelength Division Multiplexing (DWDM) techniques will be used to put all the IF data from each antenna on a single fibre. This solution will be implemented using industry-standard components and techniques as far as possible. The use of WDM makes the "patch panel" between the fibres from a few hundred, antenna pads and the 64 inputs to the correlator more manageable.

Figure1 illustrates the proposed link design.
Figure 2 defines the meaning of the symbols used and shows example parts and their characteristics.
Each fibre link from antenna to correlator will have 12, 10Gbps optical transmitters at different assigned wavelengths. A DWDM multiplexer will combine the 12 different wavelengths and feed them onto a single, standard SSMF optical fibre[2].
At the correlator, there is an optical amplifier, used to overcome attenuation and system impairments. It will have a power/wavelength monitor that will be integrated into the system control. A DWDM demultiplexer will feed 12 PIN photodetectors through a triple 4x4 optical switch. The optical switches are non-standard and will be made up from component parts as specials. They can be configured, in normal mode, to allow polarisation band pairs (on 3 wavelengths) to be swapped with one another or to allow a particular polarisation band pair to be sent to all four correlator inputs.
There will be a few hundred possible locations for the 64 antennas, containing the optical transmitters. The fibres from each of the antenna pads are connected, at the correlator housing to a central patch panel. Here, the 64 through connections will be made from the optical transmission equipment at the antennas to the optical receiving equipment at the correlator.

Proposed Design for the Baseline Fibre Optic Links

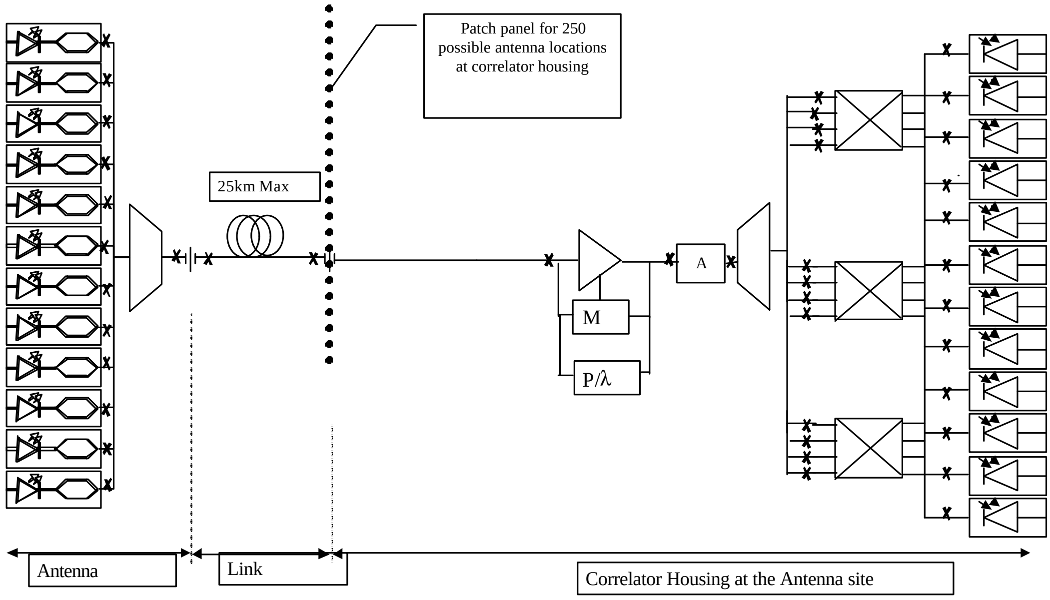


Figure 1. Baseline Link Design

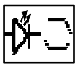
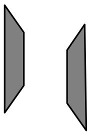
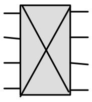
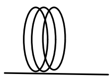
Symbol	Description	Example	Typical Characteristics
	10Gbit/sec Externally modulated transmitter	Lucent E2500 range	Typical output = 0-1dBm
	10Gbit/sec Receiver	Lucent R2860 Range – R192 STM 64	Typical Sensitivity (ideal) PIN = -18dBm, APD –24dBm Optically pre-amplified in the presence of noise assume figures given in text
	Dense DWM (De)Multiplexer	JDS Uniphase WD15016 (Thin Film Filter, TFF) Kymata Array Waveguide (AWG)	Typical Insertion Loss = 8dB Typical Insertion Loss = 5.5dB (flat band)
	Erbium Doped Fibre Amplifier (EDFA)	Ericsson PGE 60821 double pump	Typical Gain = 23dB Maximum output = 17dBm
M	Amplifier Monitor	Integral to the EDFA	
	Optical Switch	TBD	Typical quoted Insertion loss = 7.5dB
A	Optical Attenuator	Corning Eclipse VOA 0M010	Typical Insertion Loss =1dB (with splices)
	Optical Fibre	Corning SMF 28	Typical Insertion Loss = 0.25 + 0.05dB corresponding to a splice every 2km = 0.3dB/km
	Splice		Typical Insertion Loss for SMF = 0.1dB
	Connector		Typical Insertion Loss = 0.9dB
P/ λ	Power & Wavelength Monitor	JDS Uniphase - Waveguide Monitor	

Figure 2. Key to Baseline Link Design

Design Calculations

Optical signal transmission systems, like all others, are subject to system impairments. This section will look at these system impairments and their impact on the signal to noise ratio at the receiver.

Attenuation

Figure 3 shows the total system attenuation, based on estimated values for the various system components. The table illustrates that the addition of an optical amplifier into the design will significantly reduce the total system attenuation. A 6dB start of life margin has been added to the power budget to accommodate component degradation over time.

Network Elements	Fibre distance km	+switch +amp Loss dB	+switch No amp Loss dB	distance dependant loss db
Laser Output (dBm)		0	0	
Splice		-0.1	-0.1	
Connector		-0.1	-0.1	
WDM combiner + connectors		-7.5	-7.5	
Splice		-0.1	-0.1	
array cable in trench 1 splice/2km	25	-7.5	-7.5	0.3
Splice		-0.1	-0.1	
Patch panel connectors		-0.2	-0.2	
Input Into Amplifier (connectorised)		-15.6	-15.6	
Amplifier Output (dBm) (connectorised)		6	-15.6	
WDM demux + connectors		-7.5	-7.5	
Splice		-0.1	-0.1	
Switch + connectors		-7.5	-7.5	
Splice		-0.1	-0.1	
Connector		-0.1	-0.1	
Margin		-6	-6	
Total Attenuation over the link		-15.3	-36.9	

Figure 3. An estimate of total attenuation over the optical link

Dispersion

Dispersion in fibres causes pulses to spread in transmission. This spreading affects the bit error rate at the receiver as the pulses interfere with one another creating noise called Intersymbol Interference (ISI). The penalty to the SNR at the receiver can be quantified using a number of methods[3,4,5].
Using Ramaswami [3] we will assume that the pulse spreading due to chromatic dispersion should be less than a fraction $\in$ of the bit period.
For a power penalty of 1dB $\in = 0.306$
For a power penalty of 2dB $\in = 0.491$

Assuming no chirp on the pulses and a negligible spectral width (eg. An externally modulated DFB laser) then:

$$B\lambda\sqrt{\frac{|D|L}{2\pi c}} < \in$$

B = Bit Rate ; 10Gbit/sec
λ = 1.55μm
L = Link length ; 25km
c = 3x 10^8 m/s
D = 17ps/nm.km for SSMF fibre

When L = 25km $\in = 0.233$ for SSMF, therefore we can assume a 1dB noise penalty due to dispersion over the baseline link lengths, in the ideal case. In reality, the electroabsorbtion-modulated lasers (EML) that will be used on the optical transmitter boards will induce some chirp onto the signal. Generally these practical components will be rated for a maximum 2dB dispersion penalty under specified operating conditions and over a specified link length. Therefore we will assume a maximum of 2dB dispersion penalty induced by fibre dispersion and signal chirp.

Polarisation Mode Dispersion[3] (PMD)

Polarisation in single mode fibres can cause intersymbol interference and is responsible for 'fading' of the signal over digital transmission systems. The phenomena is cumulative and is calculated using averaged values by the equation:

$$\Delta t = D_{PMD}\sqrt{L}$$

$\Delta\tau$ is the time averaged differential time delay
L is the Link Length
D_{PMD} id the fibre PMD parameter

During normal operation the system will not incur a power penalty due to PMD if the condition shown below is met:

$$\Delta t = D_{PMD}\sqrt{L} < 0.1T$$

T is the time period of the pulses and is B^{-1} = 100ps
For good quality SSMF D_{PMD} = 0.1ps/√km.
According to equation, for a 25km link $\Delta\tau$ = 0.5ps << 10ps

The cabling process is likely to increase the values of D_{PMD}, thus increasing the overall link polarisation mode dispersion. It is unlikely however that the cabling process will increase the PMD tenfold.
The PMD value of cabled fibre should be discussed with the cable manufacturer at the tender stage.
For the purposes of design the PMD power penalty can be assumed negligible for transmission over 25km of SSMF fibre.

Polarisation Dependent Loss (PDL)[3]

Some components in the network will be polarisation sensitive and have some polarisation dependent loss. When choosing components it is important to choose ones with a low value of polarisation dependent loss. This will prevent a large system impairment in the worst case where interfering signals have identical polarisations. At this stage we will leave a 3dB margin for PDL across the link.

Non-Ideal extinction ratio of the transmitter[3]

If the extinction ratio of the transmitter is non ideal then the difference between the 1 and 0 levels is reduced at the receiver and thus produces a power penalty. The power penalty due to a non-ideal extinction ratio is:

$$PP_{sig\text{-}indep} = -10\log\{(r-1)/(r+1)\}$$

Where r = extinction ratio.

Assuming an externally modulated source with an extinction ratio of 10dB will give ~ 1dB power penalty.

Crosstalk[3]

In a multichannel link comprising filters, multiplexers, switches etc.. it is inevitable that one signal will effect another causing crosstalk. This is due to non-ideal extinction between one channel and another.
Interchannel crosstalk is caused by a signal outside the electrical bandwidth of the receiver. Intrachannel crosstalk is caused by a signal inside the electrical bandwidth of the receiver. For systems where the dominant noise component is the receiver thermal noise as is the case here, the power penalty due to intrachannel crosstalk is given by:

$PP_{sig\text{-}indep} = -10\log(1-2\sqrt{\in_x})$

Where $\in_x P$ is the crosstalk level in a channel with average received power P. The power penalty for interchannel crosstalk is given by:

$PP_{sig\text{-}indep} = -10\log(1-\in_x)$

Components should be chosen to reduce the amount of crosstalk in the link. A typical crosstalk value from commercially available DWDMs is less than –20dBm.
It is likely that a significant proportion of the system crosstalk will arise in the switch. Values of crosstalk we anticipate here are difficult to quantify, since it will be a custom made component. If we assume a worst-case value of –20dB crosstalk at the switch, then the power penalty due to cross talk will be 1dB.

Non-Linear effects[3,8].
Non-Linear effects occur in fibre links when the transmitted power along the link reaches a threshold power. This is only likely to happen at the output of an optical amplifier. Non-Linear effects include:

- Scattering effects
    - Stimulated Raman Scattering
    - Stimulated Brillouin Scattering
- Kerr Effect
    - Four Wave Mixing
    - Self Phase Modulation
    - Cross Phase Modulation

Since the fibre attenuation will diminish the power as it travels along the fibre, the non-linear effects take place over the effective length of the fibre L_{eff} given by the equation:

$$L_{eff} = \frac{1-e^{-\alpha L}}{\alpha}$$

for $\alpha L >> 1 \quad L \sim \alpha^{-1}$
Where α = fibre attenuation and L = Link Length.
In the baseline case the optical amplifier is at the receiver and therefore L_{eff} = 0km and non-linear effects will be negligible.

Receiver Sensitivity Calculations[3,4]

The design parameter Q is a measure of the ratio of the average signal current to r.m.s noise at the output of the photo-receiver. Q is a measure of electrical signal to noise and can be converted to dB units using the equation $Q_{dB} = 20\log Q_{lin}$.
Q value is calculated from the desired Bit Error Rate (BER) from the equation:

$$BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right) = \frac{\exp(-Q^2/2)}{Q\sqrt{2p}}$$

In the case of the baseline ALMA system a BER of 10^{-6} is required.
In the absence of signal impairments this corresponds to an ideal Q value of 5 in linear units or 14dB.
Figure 4 shows a summary of power penalty assignments for the various system impairments and the total required system Q value for a BER of 10^{-6}

Impairment	**Power Penalty Allocation (dB)**
Dispersion	2
PMD	Negligible
Non-Ideal Transmitter	1
PDL	3
Crosstalk	1
Non-Linear Effects	Negligible
Ideal Q for 10^{-6} BER (dB)	14
Total Q (dB)	21
Total Q (linear)	11

Figure 4. Summary of power penalties

The Q factor is used to calculate P_{rec}, the required optical signal power in the presence of noise at the photo receiver. P_{rec} is also called the receiver sensitivity.
In the ALMA link thermal noise, shot noise, spontaneous – spontaneous beat noise and signal-spontaneous beat noise (the last two, added by the presence of an optical amplifier) will all be generated in the system. All these noise components , except thermal noise are signal dependent. In the case of the ALMA links, the presence of a de-multiplexer and an optical switch before the receiver renders the signal dependent noise components negligible. Figure 5. shows the levels of noise at the receiver vs optical input power. From the graph we can see that above signal levels of ~ -11dBm signal dependant noise dominates. Here we assume that because the input signal at the receiver will be ~ -15dBm (see Table 1.), that the receiver is thermal noise limited.

Noise related to input power

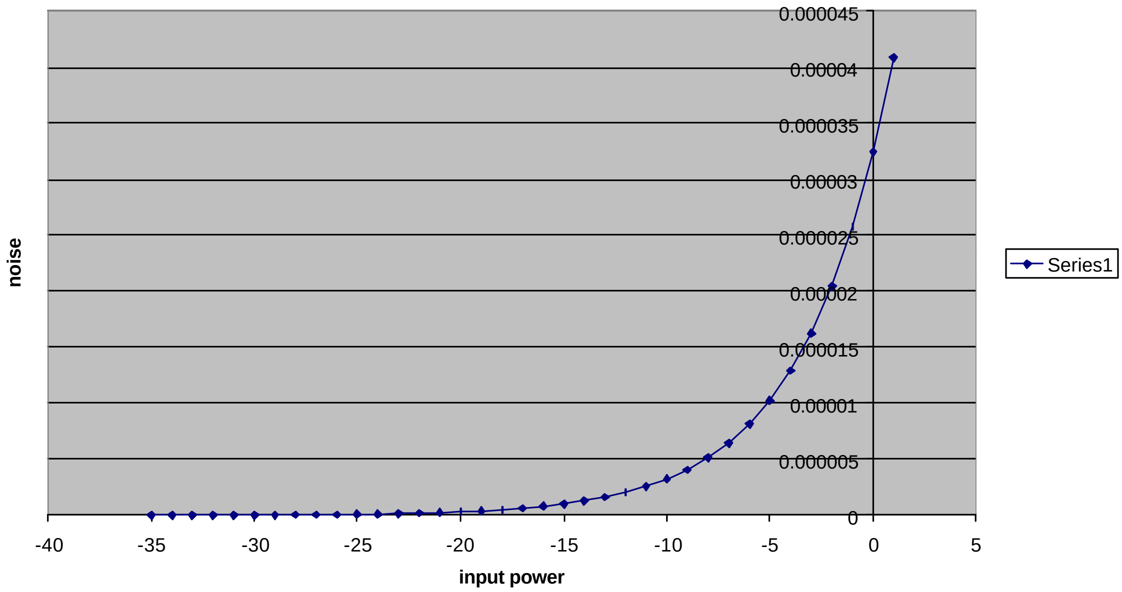


Figure 5. Noise vs Input power (dBm)

The minimum received power P_{rec} for a thermal limited receiver is given by the equation[4]:

$P_{rec} \approx Q\sigma_T/$

Where is the responsivity of the pin diode = 0.8 A/W
And σ_T is the thermal noise and can be calculated from the equation

$$\sigma_T = \frac{4K_B T}{R_L}\Delta f$$

where K_B is boltzmans constant = 1.38×10^{-23}
T is temperature in Kelvin = 298K
R_L is the load resister and has a typical value of 100Ω
Δf is the effective noise Bandwidth typical Bit Rate/2 = 5GHz
When Q=11, as calculated earlier $P_{rec} =$ -19.04dBm

Power Budget

The power budget for this system, shown in Figure 6 is a summary of all the system calculations including system margin, attenuation, dispersion etc. and the calculated receiver sensitivity. The power budget shows that this link has an additional 3.74dBs of margin over and above the 6dB lifetime margin already included in the budget. This link is technically feasible and will work under the circumstances described here.
Practical implementation of this system in the lab will test this theory.

Network Elements	Fibre distance km	+switch +amp Loss dB	+switch No amp Loss dB	distance dependant loss db
Laser Output (dBm)		0	0	
Splice		-0.1	-0.1	
Connector		-0.1	-0.1	
WDM combiner + connectors		-7.5	-7.5	
Splice		-0.1	-0.1	
array cable in trench 1 splice/2km	25	-7.5	-7.5	0.3
Splice		-0.1	-0.1	
Patch panel connectors		-0.2	-0.2	
Input Into Amplifier (connectorised)		-15.6	-15.6	
Amplifier Output (dBm) (connectorised)		6	-15.6	
WDM demux + connectors		-7.5	-7.5	
Splice		-0.1	-0.1	
Switch + connectors		-7.5	-7.5	
Splice		-0.1	-0.1	
Connector		-0.1	-0.1	
Margin		-6	-6	
Receiver sensitivity		19.04	19.04	
Power Budget		3.74	-17.86	

Figure 6. System Power Budget.

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10. ALMA Memo 380, The correlator at the OSF?, Roshene McCool, Bryan Anderson , Jodrell Bank Observatory, University of Manchester, UK.

APPENDIX A –List of Abbreviations

1.	$\in$	Fraction of pulse spread or crosstalk
2.	λ	Wavelength
3.	α	Fibre Attenuation
4.	η	Efficiency
5.	τ	Pulse width
6.	$\Delta\lambda_S$	Channel spacing (nm)
7.	ω_I	Frequency (i)
8.	A_e	Effective Area
9.	ALMA	Atacama Large MM Array
10.	APD	Avalanche Photo Diode
11.	AWG	Array Waveguide
12.	B	Bit Rate
13.	B_e	Electrical Bandwidth
14.	BER	Bit Error Rate
15.	c	Speed of light in a vacuum = $3x10^8$
16.	D	Chromatic Dispersion
17.	D_{PMD}	Fibre Polarisation Mode Dispersion
18.	EDFA	Erbium Doped Fibre Amplifier
19.	f_c	Carrier Frequency
20.	FWM	Four Wave Mixing
21.	G	Amplifier Gain
22.	h	Plank'sconstant = $6.63x10^{-34}$J/Hz
23.	ISI	Intersymbol Interference
24.	L	Length
25.	L_{eff}	Effective Length
26.	L_{NL}	Non Linear Length
27.	N	Number of channels
28.	n	Intensity dependent refractive Index
29.	NF	Amplifier noise figure
30.	n_{sp}	Spontaneous emission constant
31.	NZ-DSF	Non-Zero Dispersion Shifted Fibre
32.	P	Power
33.	PDL	Polarisation Dependent Loss
34.	PMD	Polarisation Mode Dispersion
35.	PP	Power Penalty
36.	P_{rec}	Receiver Sensitivity
37.	P_{th}	Threshold Power
38.	r	Extinction Ratio
39.	SBS	Stimulated Brilluoin Scattering
40.	SSMF	Standard Single Mode Fibre
41.	SNR	Signal to Noise Ratio
42.	SPM	Self Phase Modulation
43.	SRS	Stimulated Raman Scattering
44.	T	Time period of a pulse
45.	TFF	Thin Film Filter
46.	XPM	Cross Phase Modulation

Appendix B -Safety of the ALMA IFDTS Links

The laser light used in the data transfer system for ALMA is potentially hazardous to the human eye and this type of optical system is governed by international standards.
Relevant standards in this area are :

- The Safe Use of Optical Fiber Communication Systems Utilizing Laser Diode and LED Sources - American National Standard (ANSI Z136.2).
- Safety of Laser products – Part 2. Safety of optical fibre Communications systems – International Electrotechnical Commission (IEC 60825 –2).

The IEC recommendations apply under foreseeable fault conditions whereas the American standards apply to normal operating conditions. In practice, this means the IEC standard is the more stringent of the two and will be applied here.

Defining the ALMA IFDTS safety risks.

The safety risks at each stage of the ALMA IFDTS can be defined by:

- location type,
- failure mechanisms and
- hazard levels

Location Type

There are three types of location as defined in the IEC document

1. *Location with controlled access* – location where access to the protective housing (enclosure) is controlled and is accessible only to authorised persons who have received adequate training in laser safety and the servicing of the system involved. Examples include optical cable ducts and switching centres.
2. *Location with restricted access* – location where access to the protective housing (enclosure) is restricted and not open to the public. Examples include industrial and commercial premises.
3. *Location with unrestricted access* – location where access to the protective housing (enclosure) is unrestricted. Examples include domestic premises and premises open to the public.

Under these definitions the ALMA IFDTS can be defined as a controlled access location if simple precautions are taken such as:

- Use interlocked cabinets for all laser emitting equipment,
- install locks on all fibre enclosures
- implement user training for all personnel with access to system keys
- Clear and thorough guidelines for working practices in installation, maintenance, test and operation.

Failure Mechanisms

Hazard levels are defined in IEC 60825 under *reasonably foreseeable events*. A reasonably foreseeable event is one that can be predicted fairly accurately and the occurrence probability is not low or very low. Examples of reasonably foreseeable events are:

- component failure
- fibre cable break
- optical connector disconnection
- operator error or
- inattention to safe working practices.

Reckless use or use for completely inappropriate purposes is not considered as a reasonably foreseeable event.

Detailed hazard and safety analysis of the system are strongly recommended by the standard. Where optical output is dependent on the integrity of components and the integrity of circuit design, the recommendation suggests fault analysis down to circuit level using methods such as failure modes effects and criticality analysis (FMECA).

Hazard Level

Hazard levels are allocated to accessible locations within the fibre optic system based on the level of optical radiation that could become accessible in reasonably foreseeable circumstances, e.g. a fibre cable break.
Hazard levels are defined in IEC 60825-2 in terms relating to fibre systems. These definitions are closely related to the laser classifications detailed in IEC 60825 –1.
The hazard levels applicable to 1500nm range are listed below with their related upper limit optical powers calculated using worst-case single mode fibre.

- Hazard Level 1 – 10mW
- Hazard Level 3A – 50mW
- Hazard Level *k* x 3A – 54mW
- Hazard Level 3B – 500mW

The laser modules used in the system are classed as 3B lasers and have a maximum output of 10mW, under fault conditions.
The multiplexer at the laser outputs will combine and therefore increase the laser hazard levels at it's output. Under fault conditions, that see all 12 lasers at maximum output there is potential for a combined power of ~120mW, (less multiplexer attenuation) at the output of the multilexer. In the condition that the faulty link is in a location at a very short distance from the OSF, there is also the potential for class 3B laser light at the output of the patch panel.
The fault conditions described here will be precipitated by circuit failure at the transmitter. It is important, therefore that the probability for such a fault occurring is examined in detail.

Standard EDFA modules are rated as class 3B lasers. The maximum hazard level in the system will therefore be Level 3B, at the output of the EDFAs. The gain of the EDFA is shared across all channels. If all but one channel fails then the single remaining channel will see maximum gain through the EDFA. It is possible, in these circumstances that a single channel will have a power of 17dBm at the output of the EDFA. In these fault conditions one of the outputs of the demultiplexer, could be, hazard level 3B.

Figure A below shows the hazard levels defined for the ALMA baseline link.

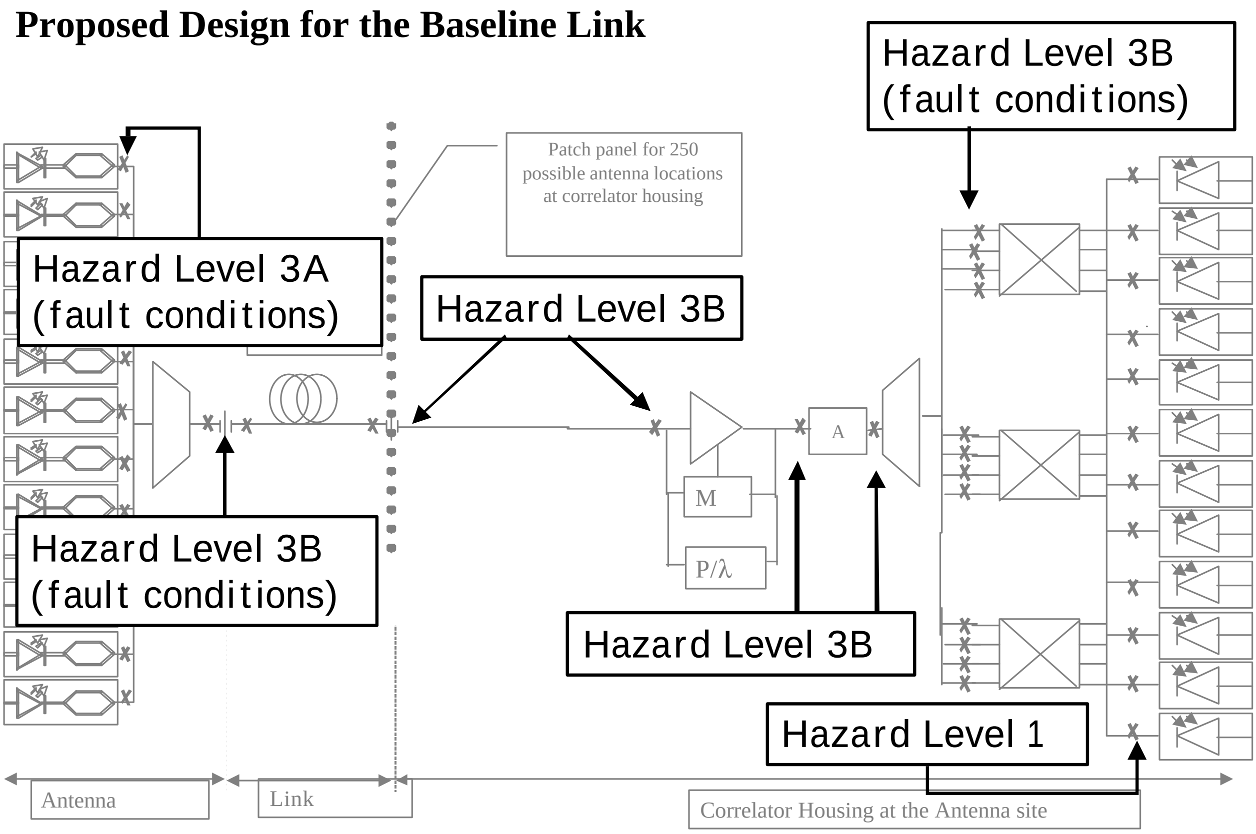

Figure B. Location of hazard levels for the baseline design

Design response to Hazard levels

IEC 60825-2 has a number of recommended precautions that should be implemented in response to the hazards describe above. This section deals with how these recommendations impact specifically on the ALMA baseline design.

Automatic Power Reduction

There are two main areas of hazard in the ALMA baseline design. These are:

1. Output of the transmitters
2. Output of the EDFAs

Both these outputs will be monitored in a local control loop and automatic power reduction systems will be implemented for both cases. Shutdown will

occur in the case of power levels outside normal operating conditions. These systems will have a maximum response time of 3s.
In addition, shutdown of the transmitters should occur when antennas are moved around the site. Procedures and safeguards will be implemented to ensure this is the case.

Labelling

- Optical fibre cables should carry appropriate markings to distinguish them from cables carrying other services e.g. electricity.
  We should consider distinguishing IFDTS fibre *within* fibre cables if they are the only potentially hazardous fibres in the ALMA optical infrastructure.
- A yellow laser warning label will be associated with each optical connector if the hazard level at the location is in excess of hazard level1.
- Groups of connectors such as patch panels may be labelled as a group, with just a single clearly visible location hazard label rather then having each connector individually labelled. If a group of connectors is enclosed within a box, a label will be clearly visible both before and after the access panel is opened.

Provision of information

The optical fibre communication system and subassemblies will require the following information, where applicable, to abide by the IEC recommendations:

- An adequate description of the engineering design features incorporated into the product to prevent access to hazardous levels of optical radiation.
- Adequate instructions for proper assembly, maintenance and safe use, including clear warnings concerning the precautions to be taken in order to avoid possible exposure to hazardous radiation.
- A statement, in SI units, of the power propagating in the fibre at all locations in the system, together with the maximum modulation frequency. The cumulative measure of uncertainty and any expected variation in the measured quantities with time shall also be provided.
- A statement of the range of operating wavelengths within the optical fibre communication system at the time of manufacture and under specified conditions as well as the range of emission wavelengths expected to occur during normal operation at any time after manufacture.
- The reaction time of any automatic power reduction system.
- Legible reproductions of all labels and hazard warnings to be displayed at locations within an optical fibre subassembly, as appropriate.
- A clear indication of all locations of apertures and fibre connectors.
- A listing of controls, adjustments and procedures for operation and maintenance, including a warning where appropriate.
- Advice on safe operating procedures and warnings concerning known malpractices, malfunctions and hazardous failure modes. Where

maintenance procedures are detailed they shall, wherever possible, include explicit instructions on the safe procedures to be followed.

- Where installation or servicing requires that an automatic power reduction system is overridden, information to enable the operating organization to specify a safe system of work at such times, and a safe procedure for the reinstating and safe testing of the automatic power reduction system.