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ALMA Memo 349
Fibre-Optic Link Design of the Atacama IF Data Transfer System.

Executive Summary

This report examines the designs for two possible data links for IF signal transfer from the ALMA antennas to the data correlator. The first design is for the case where the correlator is located on the array site. The second design is for the case where the correlator is located at or near San Pedro, perhaps some 70km away, by fibre, from the array site.

The main focus of the report is the technical feasibility or otherwise of the options. The report also provides some of the information from which the better option, from a systems point of view, can be selected. No estimates of costs are provided. Proper costings will be provided in a forthcoming companion report together with recommendations of actual components. This part of the whole is being released so that the ALMA community can assess the technical arguments which justify a necessary but modest increase in costs for IF data transfer.

The following points are the main conclusions of the study:

- Both links are technically feasible using industry-standard components over standard single-mode fibres.

- Optical fibre amplifiers are required immediately ahead of the correlator for both possible links to overcome the losses and impairments of the signal. This need was not envisaged previously and it will necessitate an increase of funding in this area.

- It is difficult to provide accurate costs because vendors of 10 Gbit/sec components are presently unwilling or unable to provide quotations for the components they advertise.

- If the correlator were to be housed at the array site then the fibre-link procurement costs would be minimised. However, the optical receivers, correlator and ancillary test equipment would be operating outside the altitude ranges specified in data sheets, and overall construction and maintenance costs would not necessarily be minimised.

- For the "San Pedro" option, a second set of identical optical amplifiers would be required at a convenient "central" point in the array. These amplifiers would probably occupy two 19" racks and dissipate in total less than 1 kW. The central facility would also house the "patch panel" by which connections from the antennas pads to the correlator can be made.

    - The additional resources required for a link between Chajnantor and San Pedro are:

        - 64 optical amplifiers + monitor and control.
        - 64 fibre cable + monitor and control fibres.
        - Possible requirement of dispersion compensation. This is not a major issue.

    - These resources might be reduced by concentrating the signals from two or more antennas on one fibre. More work on this option has been recommended.

    - For this option, the amount of equipment on site would be minimised and overall building, installation and maintenance costs might be lower. However, this link would require more optical amplifiers which would be located at the array site and the fibres would need to be extended.

Contents

1 Introduction

This document is designed to provide to all project participants as much information as possible on the design of a fibre-optic link for IF data transfer. The "baseline" data transfer system has to carry 8 (4 bands, 2 polarisations, each 2GHz wide) data streams at 12 giga-bits per second (Gbps) each from an antenna to the signal correlator. A maximum transmission distance of 25km is assumed. The 2GHz-wide bands are digitised to 3 bits of precision at the 4GHZ Nyquist rate.

Provisional design decisions were to use twelve 10 Gbps optical transmitter-receivers combinations to carry these signals, to employ wave-division multiplexing (WDM) to put all the IF data from each telescope on a single fibre and to use industry-standard components and techniques as far as possible. The use of WDM makes the "patch panel" between the fibres from 250 antenna pads and the 64 inputs to the correlator more manageable.

A number of people have suggested that there may be advantages in extending the optical fibres so that the correlator could be located at a lower altitude, perhaps even in San Pedro, some 70km from the antenna site. The economic arguments for and against this proposal will be addressed in a later document but both proposals, the "baseline" and the "San Pedro" are included in this study.

The use of industry-standard 10 Gbps components is not as straightforward as it might initially seem. Manufacturers may have (provisional) specification sheets on their web sites, but this does not mean they have the products to sell. Many manufacturers are also unwilling to give budgetary quotes, which they perceive as commercially-sensitive information, for the purposes of design. Perhaps order books are full at the moment. There is also a worldwide shortage of fibre and cable manufacturers are unwilling to quote for cable prices. The difficulty of getting potential suppliers to quote for components may well change when there are potential orders closer at hand. For these reasons, budgetary estimates will be put in a separate, later document.

The design process is an iterative one. This document is the first step in that process. It is not intended to be the final link design, but rather a first sketch upon which to build. Further simulation and examination of the topics included here will be the subject of more work over the lifetime of the project.

References are made in this document to good standard texts on this subject. Please refer to these texts for more detailed explanations of the topics touched on in this document. This report follows the standard fibre-optic practices described in these references. In particular, some effects in the fibre and components result in reductions, impairments, in the abilities of the receivers to reconstitute the digital signals with prescribed error rates. These are handled by requiring larger-than-nominal signal strengths at the receivers. Most of the calculations used in the design process can be found in Appendices C to H.

2 Link Alternatives

Figures 2.1 and 2.2 are sketches of the proposed link designs. The first is for the baseline system and the second is for the San Pedro option. Both anticipate the results of this study (see Section 3) and use optical amplifiers to overcome system losses and impairments. Figure 2.3 defines the meaning of the symbols used and shows example parts and their characteristics.

In both sketches, there are 12 laser-diode-modulators and 12:1 (probably 16:1) DWDM multiplexers which combine the 12 different wavelengths and feed the optical fibres. Optical attenuators may be required between the laser-diode-modulators and the combiner so that the output levels from the transmitter can be carefully equalised for the optical amplifiers.

In both systems, at the correlator, for each input fibre, there is an optical amplifier, possibly with a power/wavelength monitor, and a 1:12 DWDM demultiplexer which feeds 12 PIN photodetectors through a triple 4x4 optical switch. The optical switches are non-standard: 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. The power/wavelength monitors would be used to monitor the performance of the laser-diode transmitters.

For both systems, the fibres from antenna pad are taken to an on-site central patch panel. The chosen 64 outputs in the San Pedro option are optically amplified locally and then connected by fibre down the mountain to the optical preamplifiers ahead of the correlator. In the baseline option, there would be a direct connection from the patch panel to the optical preamplifiers. It is likely that the optical amplifiers and preamplifiers will be identical devices.

Fig 2.1 Proposed Design for the Baseline Link

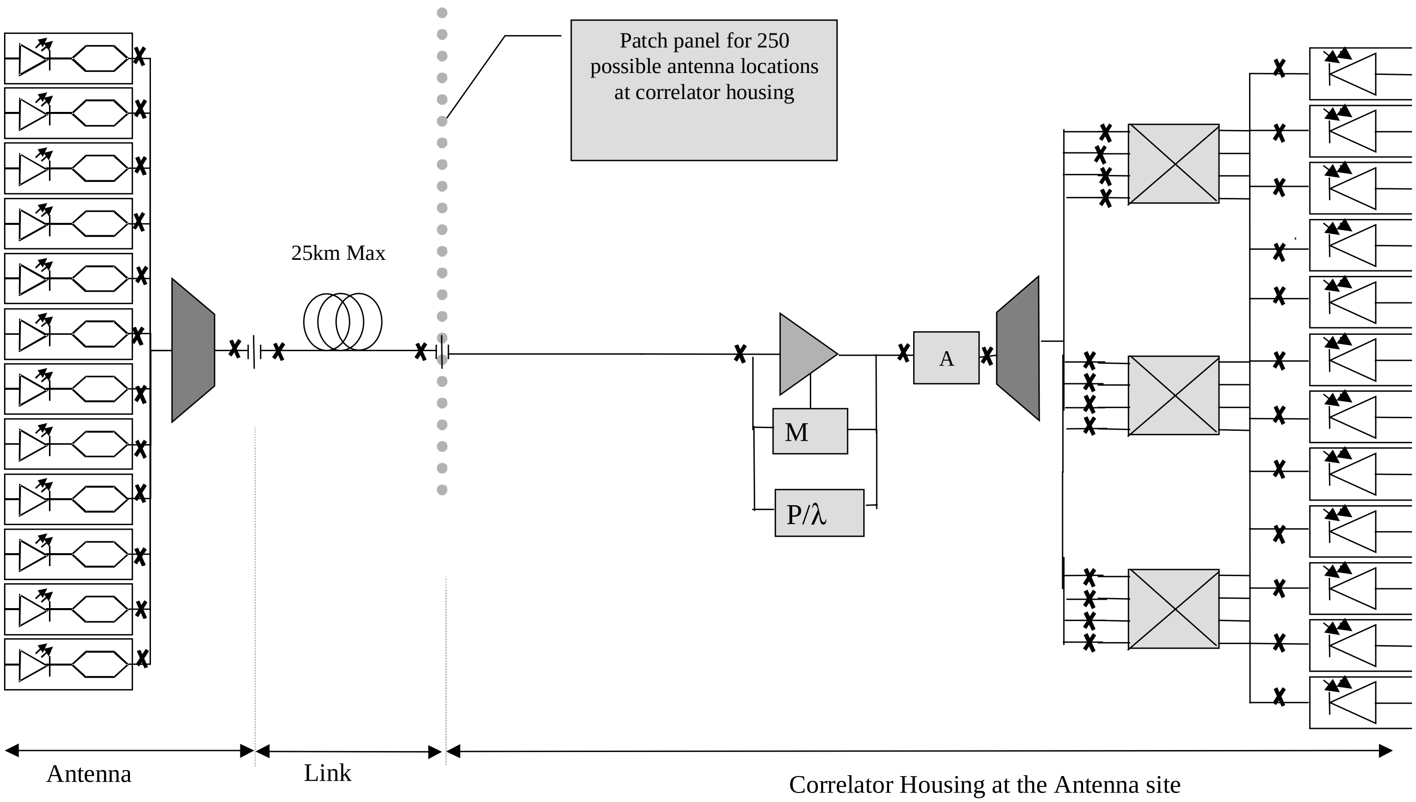
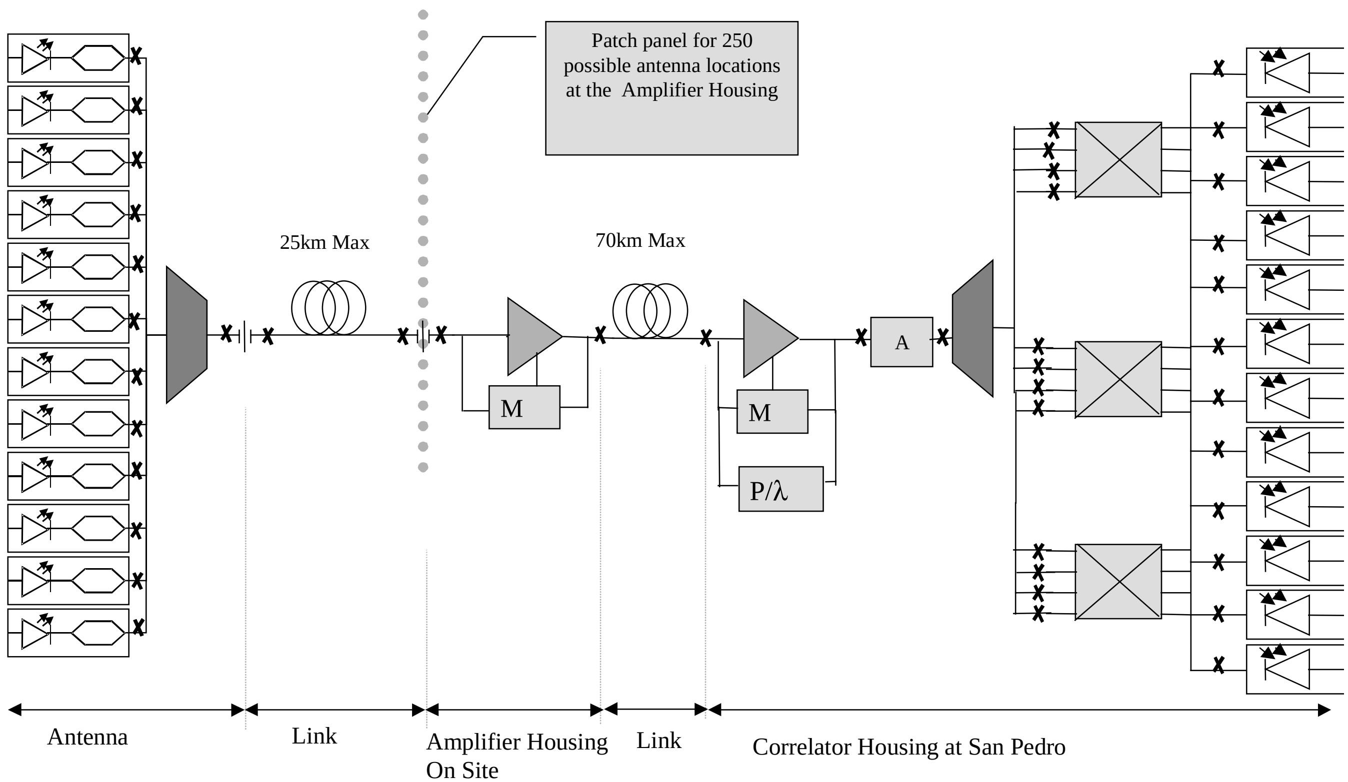


Fig 2.2 Proposed Design for the link to San Pedro



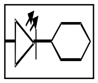
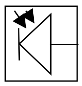
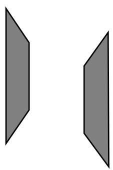
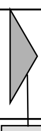
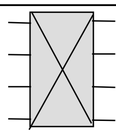
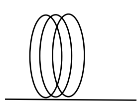
Symbol	Description	Example	Typical Characteristics
	10Gbit/sec Externally modulated transmitter	Lucent E2500 range	Typical output = 0-1dBm
	10Gbit/sec Receiver	Lucent R2860 Range – R192 STM 64	Typical Sensitivity (ideal) PIN = -18dBm, APD –24dBm Optically pre-amplified in the presence of noise assume 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	

Fig 2.3 Key for previous link sketches

3 Justification of the use of Optical Amplifiers

For the baseline, 25km link, using the component values described in Fig2.3 the loss within the link will be greater than the achievable receiver sensitivity for typical PiN diodes. Fig 3. shows the shortfall in the power budget for the link.

Fig 3 Power Budget for the Baseline link without the use of an optical amplifier

Network Elements	Fibre distance km	Loss dB	distance dependant loss db
Laser Output (dBm)		0	
Splice		-0.1	
WDM combiner		-5.5	
Splice		-0.1	
Connector antenna to pad		-0.9	
Splice		-0.1	
array cable in trench 1 splice/2km	25	-7.5	0.3
Splice		-0.1	
Connector Link to Correlator Housing		-0.9	
Splice		-0.1	
WDM demux		-5.5	
Splice		-0.1	
Switch		-7.5	
Splice		-0.1	
Receiver Sensitivity		28	
MARGIN		-6	
Power Budget		-6.5	

For this reason an optical amplifier at the receiver has been used in the link design to over come the loss in network components.
For the San Pedro link the loss will be greater because of the extra fibre loss. Here an in-line amplifier is required to overcome the additional link loss. Appendix I shows an alternative design link budget where the correlator is housed halfway between the site and San Pedro.

4 Link Design Calculations[1]

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 and can be calculated from the desired Bit Error Rate (BER). 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.
Generally telecom networks are designed to perform at 10^{-9} BER or better. In general, today's radio telescope systems work at a rate of 10^{-5} or better. The required BER for the ALMA network has not, yet, been specified. For the purposes of the design work we will assume a BER performance of 10^{-6}. This is assumed the minimum value of BER required. At BER higher than this value, there will be some margin for error in the design calculations and for performance drift of the network over time.

The procedure for calculating the required signal level at the receiver is as follows:

- First, the ideal Q factor for a BER of 10^{-6} is calculated (Section 4.1)
- Then the additive noise from each of the known system impairments is calculated (Section 4.2, Appendices C-H).

- The required value of Q for a BER of 10^{-6}, in the presence of system noise is calculated (Section 4.2)
- This value is used to calculate the required signal level (receiver sensitivity) for a BER of 10^{-6} in the presence of system noise (Section 4.3).

4.1 Q factor for an ideal system[2]

The Q factor for a specific BER can be evaluated using equation 4.1.1 below (assuming an optimum decision threshold at the receiver):

$$BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right) = \frac{\exp(-Q^2/2)}{Q\sqrt{2\pi}} \qquad \textbf{4.1.1}$$

For a BER of 10^{-6} the Q factor can be numerically evaluated and is equal to 5.
For a BER of 10^{-5} the Q factor is equal to 4.
This value of Q is for a link without any system impairments. In the presence of noise, Q will suffer a power penalty. Appendices C-H show the calculation of power penalties associated with common system impairments.

$$Q(dB) = 20\log_{10}Q \qquad \textbf{4.1.2}$$

4.2 Summary of power penalty budgets for system impairments

The Table 4.1 shows the calculated power penalties associated with the different system impairments.

Over the 95km ALMA link the power thresholds to induce non-linear impairments are not reached. Therefore, the power penalties due to these effects are considered negligible. The threshold at which the non-linearities will become significant is ~7mW, where SBS will begin to impact the SNR of the link.

Detail of the calculated power penalties can be found in Appendices C-H.

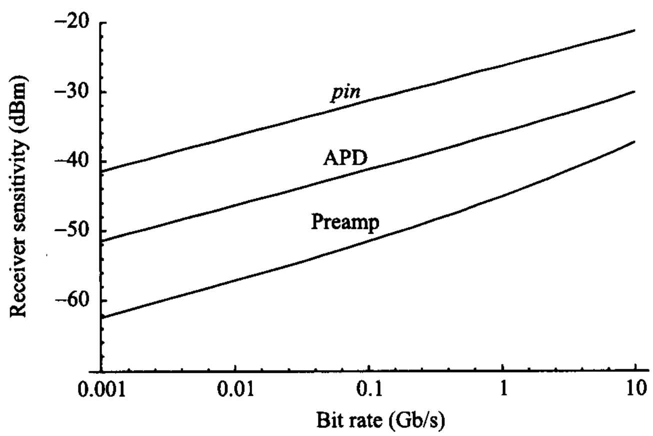
Impairment	**PP Allocation (dB) SMF**		**PP Allocation (dB) NZ-DSF**	
Link Length	*25km*	*95km*	*25km*	*95km*
Dispersion	1	2	-	-
PMD	-	-	-	-
Non-Ideal Transmitter	1	1	1	1
PDL	3	3	3	3
Crosstalk	1	1	1	1
Non-Linear Effects	-	-	-	-
Margin	*Margin to be added in final design calculations*			
Ideal Q for 10^{-6} BER (dB)	14	14	14	14
Total Q (dB)	20dB	21dB	19dB	19dB
Total Q (linear)	10	11	9	9

Table 4.1 Summary of power penalty budgets for system impairments and calculated Q

4.3 Calculation of required receiver sensitivity.

The ALMA link will have an optical amplifier at the receiver. This has the effect of changing the PiN diode from a thermal noise limited receiver to a signal dependent noise limited receiver[1]. The signal amplification by the optical amplifier increases the receiver sensitivity significantly. Fig 4.2 illustrates this.

Fig 4.2. Sensitivity plotted as a function of bit rate for typical PiN, APD and optically preamplified receivers for a BER performance of 10^{-12}.



[Source: Optical Networks, A practical perspective, R. Ramaswami & K.N. Sivarajan, Morgan Kaufmann]

The optical preamp and PiN diode are treated as one entity for the purposes of analysis.

The Q factor obeys the equation*:

$$Q = \left(\frac{\sqrt{GP}}{2\sqrt{(G-1)P_n B_e}} \right) \qquad \textbf{4.3.1}$$

Where G is the amplifier Gain
P is the received signal power
B_e is the receiver bandwidth
B= Bit rate = 10Gbit/sec

For convenience P_n is used for the term,

$P_n = n_{sp}hf_c$

* Note: Whilst this document uses equations drawn from Ref 1. we use the standard definition of Q given in equation 4.1.1. This accounts for the adjusted form of the equation in this document compared to Ref 1.

Where n_{sp} = spontaneous emission constant related to Amplifier noise figure by the equation:

$$NF \approx 2n_{sp}$$

In the case where amplifier Noise Figure = 6dB n_{sp} = 2
h = plank's constant = 6.63×10^{-34} J/Hz
f_c = Optical carrier frequency =191.3THz for a 1552.52nm optical carrier

If B_e = B/2 and the gain of the amplifier is large (which is the case here) then from eqn 4.3.1 it can be shown that :

$$Q = \left(\sqrt{\frac{M}{2n_{sp}}}\right) \qquad \textbf{4.3.2}$$

Where M is the number of photons required per bit for the specified BER

$$M = P_{rec}/hf_cB$$

Where P_{rec} = receiver sensitivity
For the worst case Q = 11 for a 95km link over SMF. In this case the required signal level at the receiver = P_{rec} = 0.61μW = -32dBm
Table4.1 is repeated here with the addition of a value of P_{rec} for the quoted value of Q.

Impairment	**PP Allocation (dB) SMF**		**PP Allocation (dB) NZ-DSF**	
Link Length	*25km*	*95km*	*25km*	*95km*
Dispersion	1	2	-	-
PMD	-	-	-	-
Non-Ideal Transmitter	1	1	1	1
PDL	3	3	3	3
Crosstalk	1	1	1	1
Non-Linear Effects	-	-	-	-
Margin	*Margin to be added in final design calculations*			
Ideal Q for 10^{-9} BER	14	14	14	14
Total Q (dB)	20	21	19	19
Total Q (linear)	10	11	9	9
P_{rec} μW	0.51	0.61	0.41	0.41
P_{rec} dBm	-33	-32	-34	-34

Table4.2. Receiver sensitivity calculated for the corresponding value of Q.

5 Fibre Choice

The system power budgets will use the above values of receiver sensitivity. It can be seen from Table4.2 that the use of NZ-DSF fibre does not make a significant difference to the system design. Since NZ-DSF will be at least double the cost of SMF it cannot be justified for the ALMA link.
As shown in Appendix D using Ramaswami[1] to calculate dispersion over the 95km link, shows it is feasible without the use of dispersion compensation. Using O'Mahony this length is reduced to ~ 75km. There is a low risk that dispersion compensation will be required for the link. This will be the subject of further work. In the event that dispersion compensation is required it is unlikely to justify the expense of NZ-DSF.

6 Power Budgets

Using figures for insertion loss, transmitter output and receiver sensitivity detailed in previous sections the following power budgets can be calculated for the amplified links. The positive value for power budget indicates the extra margin available in the system.

Fig6.1 Power Budget for the baseline link with an optical amplifier at the receiver.

Network Elements	Fibre distance km	Loss dB	distance dependant loss db
Laser Output (dBm)		0	
Splice		-0.1	
WDM combiner		-5.5	
Splice		-0.1	
Connector antenna to pad		-0.9	
Splice		-0.1	
array cable in trench 1 splice/2km	25	-7.5	0.3
Splice		-0.1	
Connector Link to Correlator Housing		-0.9	
Splice		-0.1	
Input Into Amplifier		-15.3	
Amplifier Output (dBm)		6	
Splice		-0.1	
Optical Attenuator		-1	
Splice		-0.1	
WDM demux		-5.5	
Splice		-0.1	
Switch		-7.5	
Splice		-0.1	
Margin		-6	
Receiver Sensitivity		32	
Reciever Stage Power Budget		17.6	

Fig6.2 Power Budget for the San Pedro link with an optical in-line and an amplifier at the Receiver.

Network Elements	Fibre distance k	Loss dB	distance dependant loss db
Laser Output (dBm)		0	
Splice		-0.1	
WDM combiner		-5.5	
Splice		-0.1	
Connector antenna to pad		-0.9	
Splice		-0.1	
array cable in trench 1 splice/2km	25	-7.5	0.3
Splice		-0.1	
Connector Link to patch panel		-0.9	
Splice		-0.1	
Input into amplifier		-15.3	
In Line Amplifier Output (dBm)		6	
Splice		-0.1	
Link to San Pedro 1 splice/2km	70	-21	0.3
Splice		-0.1	
Input Into Amplifier		-15.2	
Optical Pre-Amplifier Output (dBm)		6	
Splice		-0.1	
Optical Attenuator		-1	
Splice		-0.1	
WDM demux		-5.5	
Splice		-0.1	
Switch		-7.5	
Splice		-0.1	
Margin		-6	
Receiver Sensitivity		32	
Receiver Stage Power Budget		17.6	

7 Correlator Location

The decision, where to put the correlator location, is dependent on many factors. This section will discuss some of them. A wider debate on the more subjective aspects of altitude working is outside the scope of this report. Here we will consider:

- Feasibility of Fibre Link Design
- Additional cost and complication associated with a San Pedro link
- Operating components and equipment at altitude

7.1 Feasibility of Fibre Link Design & additional resource involved with a San Pedro Link

This report has shown that it is possible to build a fibre optic link from antenna to correlator housing whether the correlator is positioned at the site or up to 95km away in San Pedro.

The additional cost of the San Pedro link will be:

- up to 64 additional optical in-line amplifiers and their associated control,
- an additional 70km of 64 fibre cable ,
- additional fibres for communication & control and
- manpower/installation costs.
- Dispersion compensation may also be required, but the risk of this is low.
- Trenching will already exist up to the site for communication cables and so trenching costs will be negligible.

This cost can be reduced by using larger multiplexers at the site to multiplex 2 antenna onto one fibre. This will reduce the optical amplifiers and cable fibre count required by a factor of 2. This option is technically possible using all the technology discussed in this paper and is unlikely to lead to significant performance impairments. A further concentration of 3 antenna onto a single fibre may be possible, an investigation of this strategy should be considered as the subject of further work.

7.2 Operating components and Equipment at Altitude

All the components used within the designs here are manufactured for use in telecommunications networks, which are not generally required to operate at the altitude of the Chanjantor site. Installing the correlator at San Pedro will bring the operating conditions within those specified for these components. If the correlator is sited at the antenna site manufacturers will not guarantee operation and military spec components may be required if available at all, increasing the cost of the network significantly.

8 Further Work.

The following additional work is recommended:

- Cost Analysis of the correlator locations described here compared.
- Accurate link length surveys and rights of way assigned
- Experimental test and simulation of the theory discussed here particularly impairments associated with dispersion over 95km.
- Investigation of the monitoring and health and safety implications of using Optical Amplifiers.
- Investigation of the implications of remote control of equipment.
- Investigation of the implications of operating components and equipment at altitude
- Investigation of the technical implications of concentrating 2 or 3 antenna over a single fibre link to San Pedro and the relevant cost benefits.
- Reliability of link from the antenna site to San Pedro.

9 Conclusions

This report examined the designs for two possible data links for IF signal transfer from the ALMA antennas to the data correlator. The first design considered a correlator located on the array site. The second design considered a correlator located at San Pedro some 70km

away from the array site.
The following points are the main conclusions of the study:

- Both links are technically feasible using industry-standard components over standard single-mode fibres.

- Optical fibre amplifiers are required immediately ahead of the correlator for both possible links to overcome the losses and impairments of the signal. This need was not envisaged previously and it will necessitate an increase of funding in this area.

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- For the "San Pedro" option, a second set of identical optical amplifiers would be required at a convenient "central" point in the array. These amplifiers would probably occupy two 19" racks and dissipate in total less than 1 kW. The central facility would also house the "patch panel" by which connections from the antennas pads to the correlator can be made.

    - The additional resources required for a link between Chajnantor and San Pedro are:

        - 64 optical amplifiers + monitor and control.
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    - These resources might be reduced by concentrating the signals from two or more antennas on one fibre. More work on this option has been recommended.

    - For this option, the amount of equipment on site would be minimised and overall building, installation and maintenance costs might be lower. However, this link would require more optical amplifiers which would be located at the array site and the fibres would need to be extended.

References

1. Optical Networks – A practical perspective, Rajiv Ramaswami & Kumar N. Sivarajan, Morgan Kaufmann.
2. Fibre Optic Communication Systems 2nd Edition, Govind P. Agrawal, John Wiley & Sons
3. High Capacity Optical Transmission Explained, D.M. Spirit & M.J. O'Mahony, John Wiley & Sons
4. Optical Fibre Communications Systems, Leonid Kazovsky et al, Artech House publishers.
5. Optical Fiber Communications, Principles and Practice 2nd Edition, John M. Senior, Prentice Hall
6. Limitations on Lightwave Systems Imposed by Optical-Fiber Nonlinearities, Andrew R. Chraplyvy, Journal of Lightwave Technology, Vol8 No10, October 1990

APPENDIX A - Assumptions

1. The receiver has an optimum decision threshold
2. Cabled PMD does not exceed 1ps/√km
3. Laser Extinction ratio ≥ 10dB
4. Accumulative PDL does not exceed 3dB
5. Isolation of all network elements is > 15dB
6. The dominant noise term at the receiver is signal-spontaneous beat noise due to the optical pre-amplifier. Thermal & shot noises are considered negligible. The receiver is therefore, signal dependent noise limited.
7. The optical bandwidth of the receiver is restricted by the passband of the demultiplexer and therefore spontaneous-spontaneous beat noise is negligible.
8. The amplifier gain is large
9. $B_e = B/2$
10. A splice connection is required every 2km
11. Maximum power in any channel is < 7mW (8.5dBm)
12. Trenching costs have been absorbed by the communication cables to the site.
13. The link between the antenna site and San Pedro is reliable and not subject to a lot of disruption.

APPENDIX B -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	SMF	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 C
Dispersion[5]

Dispersion in fibres causes pulses to spread in transmission. This spreading effects 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[1,3,4].
Using O'Mahony[3] the dispersion calculation gives a maximum link length of 74km for a 2dB dispersion penalty. Using Ramaswami[1] the dispersion calculation gives a maximum link length of 111km. Since Ramaswami is the latest reference we will use this method. The O'Mahony reference is included for completeness and to illustrate there may be a low risk that dispersion compensation will be required for this link.
Using Ramaswami [1] 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:

$$B\lambda\sqrt{\frac{|D|L}{2\pi c}} < \in \qquad \textbf{C.1}$$

B = Bit Rate ; 10Gbit/sec
$\lambda = 1.55\mu m$
L = Link length ; 25km or 95km
c = 3x 10^8 m/s
D = Chromatic Dispersion

When L = 25km $\in = 0.233$
When L = 95km $\in = 0.454$ for SMF

Table C below illustrates the SNR power penalties for dispersion over 25km baseline and 95km San Pedro link length for two different fibre types , Standard Single Mode Fibre (SMF) and Non-Zero Dispersion shifted fibre (NZ-DSF).

Fibre Type	**25km**	**95km**
SMF D=17ps/nm·km	1dB	2dB
NZ-DSF D=4ps/nm·km	negligible	negligible

Table C Calculated power penalties for link length and fibre type

APPENDIX D
Polarisation Mode Dispersion[1] (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 D.1:

$$\Delta\tau = D_{PMD}\sqrt{L} \qquad \textbf{D.1}$$

$\Delta\tau$ 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 in equation D.2 is met:

$$\Delta\tau = D_{PMD}\sqrt{L} < 0.1T \qquad \textbf{D.2}$$

T is the time period of the pulses and is B^{-1} = 100ps
For good quality SMF or NZ-DSF fibre D_{PMD} = 0.1ps/√km.
According to equation D.2 for a 25km link $\Delta\tau$ = 0.5ps << 10ps and for a 95km link $\Delta\tau$ = 1 << 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 both the 25km and 95km link over both SMF and NZ-DSF fibre.

APPENDIX E
Non-Ideal extinction ratio of the transmitter[1]

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:

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

Where r = extinction ratio.

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

APPENDIX F
Polarisation Dependent Loss (PDL)[1]

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.

APPENDIX G
Crosstalk[1]

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 receive. For systems where the dominant noise component is signal dependent as is the case here the power penalty due to interchannel crosstalk is given by:

$$PP_{sig\text{-}dep} = -5\log(1-2\sqrt{\in_x}) \qquad \textbf{G.1}$$

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

$$PP_{sig\text{-}dep} = -5\log(1-\in_x) \qquad \textbf{G.2}$$

Components should be chosen to reduce the amount of crosstalk in the link. For this initial design stage a power penalty of 1dB for crosstalk is assumed.

APPENDIX H
Non-Linear effects[1,6].

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:

$$L_{eff} = \frac{1-e^{-\alpha L}}{\alpha} \qquad \textbf{H.1}$$

for $\alpha L >> 1$ $\quad L \sim \alpha^{-1}$
Where α = fibre attenuation and L = Link Length.
For long link lengths and a fibre attenuation of 0.22dB $L_{eff} \sim$ 20km
For long link lengths and a fibre attenuation of 0.3dB (including splice loss) $L_{eff} \sim$ 15km.

In the case of the 25km length the optical amplifier is at the receiver (see section 3 for justification of the use of an amplifier) and therefore L_{eff} = 0km and non-linear effects will be negligible. In the case of the 95km link we can assume that L_{eff} = 15km. The next section will calculate power penalties related to the non-linear effects over the 95km link.

The power levels, resulting in non-linear effects within the 95km ALMA link will be due to an in-line amp on the Chajnantor site. This amplifier will be housed on the antenna site. A standard in-line amplifier will have a maximum *total* output power of 17dBm. This suggests that the power per channel within the fibre will be no greater than 4mW or 6dBm at the output of the optical amplifier. The following calculations for power penalties associated with fibre non-linear transmission characteristics assume this maximum transmitted power.
Over the 95km ALMA link the power thresholds to induce non-linear impairments are not reached. Therefore, the power penalties due to these effects are considered negligible. The threshold at which the non-linearities will become significant is ~7mW, where SBS will begin to impact the SNR of the link.
More detailed justification of this conclusion is detailed in the sections below.

Stimulated Raman Scattering (SRS)[1]

SRS effects multichannel systems and is a broadband effect. The power is lost from shorter wavelength channels to longer wavelength channels. Coupling occurs only if both channels are transmitting a one. The effect is therefore reduced when dispersion is present in the system since the different channels will travel at different group velocities reducing the probability of overlap between pulses at different wavelengths at any point in the fibre.

$$PP_{SRS} = -10\log(1-P_0) \qquad \textbf{H.2}$$

Where P_0 is the fraction of the power coupled from channel 0 to all other channels. In general, the total power and the total bandwidth should be minimised in order to reduce the degradation due to SRS[6].

If N = Number of channels = 12
P = Threshold power
$\Delta\lambda_s$ = Channel spacing (nm) =100GHz or 200GHz
L_{eff} = Effective Length = 15km

For a 0.5dB power penalty P_0 <0.1 in the absence of dispersion (assumption for the NZ-DSF case) so,

$NP(N-1)\Delta\lambda_s L_{eff} < 40{,}000$ mW nm km

In this case,
P_{th} = 25mW @ 100GHz (0.8nm)
P_{th} = 12.5mW @ 200GHz (1.6nm)

Dispersion will reduce the SRS effect by a factor of two, so for a 0.5dB power penalty over SMF

$NP(N-1)\Delta\lambda_s L_{eff} < 80{,}000$ mW nm km

P_{th} = 50mW @ 100GHz (0.8nm)
P_{th} = 25mW @ 200GHz (1.6nm)

Under the baseline conditions, the power penalty due to SRS will be negligible.

Stimulated Brillouin Scattering (SBS)[6]

SBS is a back scattering effect and power of the transmitted light is lost to a scattered beam travelling towards to transmitter. This phenomenon is independent of the number of channels. The point at which SBS will degrade the systems performance is :

$$P_{th} = 21bA_e/(g_B L_{eff}) \qquad \textbf{H.3}$$

For single mode fibres $g_B=4\times10^{-9}$cm/W

b accounts for the relative polarisations of the interacting waves =2 for conventional fibres
A_e = Fibre effective area = $5x10^{-7}cm^2$ for conventional fibres
P_{th} = Threshold Power
L_{eff} = Effective Length = 15km

Using the equation above the threshold power for P_{th} = 3.5mW

SBS is caused by interaction with acoustic phonons in the fibre structure and has very long lifetimes. High modulation rates produce broad optical spectra and a reduction in the SBS amplification can be expected. It happens that at bit rates considered for the ALMA project the SBS power threshold can be conservatively increased two fold[1]. Therefore, P_{th} = 7mW.

SBS can be further reduced by increasing the linewidth of the laser (since the gain bandwidth is very small). This is achieved by dithering the laser at a ~200MHz. This will cause some dispersion penalty, but increase P_{th} by an order of magnitude. This method is used in commercial systems and it may be of interest to the ALMA project if the SBS penalty becomes significant.
For the purposes of this paper, a penalty is assumed negligible for both SMF and NZ-DSF.

Four Wave Mixing (FWM)[6]
Four wave mixing is the interaction between three transmitted channels at different frequencies $\omega_i, \omega_j, \omega_k,$ producing a fourth product frequency
$\omega_{ijk} = \omega_i + \omega_j - \omega_k$.
FWM is a product of the Kerr effect.
The FWM product reduces the energy in the transmitted channels and gives a Power Penalty at high values of transmitted power. In addition, if the resulting frequency product is within the bandwidth of another channel it will cause crosstalk at the receiver.
The effect of four wave mixing depends on the phase relationship between the interacting signals. When the phase of the signals is the same the effect is reinforced. In the presence of dispersion the group velocities of the transmitted signals is different and therefore the effect of FWM is reduced. In dispersive systems the wider the channel spacing the greater the difference in group velocity. This is illustrated in Fig H.1 the FWM efficiency η is a function of channel spacing. From Fig H.1 it can be seen that for channel spacings of 100GHz $\eta \rightarrow 0$.
In the case of the ALMA network the penalty for FWM is considered negligible for both 100GHz and 200GHz spacings over SMF and NZ-DSF.

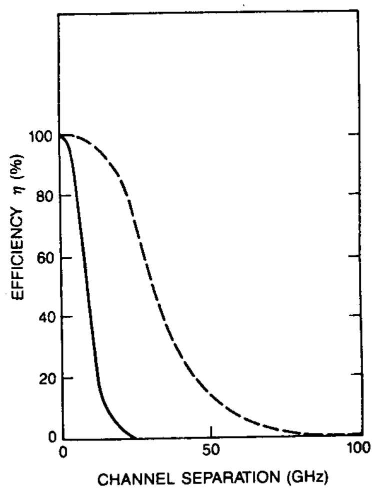


Fig H.1 Four Wave Mixing efficiency as a function of channel separation at 1.55μm. The solid curve represents Single Mode Fibre (SMF) with dispersion = 16ps/nm · km. The dashed curve is for dispersion-shifted fibre (DSF) with dispersion of 1ps/nm · km.

[Source: Limitations on Lightwave Communications Imposed by Optical-Fiber Non-linearities, A.R. Chraplyvy, JLT Vol 8 No 10, Oct 1990.]

Self Phase Modulation (SPM) & Cross phase modulation (XPM)[1]

SPM is a phenomenon, which results from the Kerr effect. The power fluctuations in the transmitted pulse are converted to phase modulations by this effect leading to chirp on the pulses. XPM is the same effect within multichannel systems where power fluctuations in one channel lead to phase fluctuations in another. For channel spacing above a few tens of GHz the power penalty due to XPM modulation is considered negligible (assuming an externally modulated source).

For SPM the following equation holds true:

$$L_{NL} = \frac{\lambda A_{eff}}{2\pi \bar{n} P_0} \qquad \textbf{H.4}$$

Where L_{NL} = Non-linear length

λ = wavelength

P_0= peak power of the pulse

$\bar{n}$ = intensity dependent refractive index factor = $3.2\text{x}10^{-8}$ $\mu m^2/W$

The chirp factor κ_{SPM} induced by SPM is

$$\kappa_{SPM} = \frac{2L_{eff}}{L_{NL}} e^{-\tau^2} (1 - 2\tau^2) \qquad \textbf{H.5}$$

Where τ is the pulse width

The SPM induced chirp at the pulse centre is bounded by the term $2L_{eff}/L_{NL}$.

The SPM induced chirp is only significant if $L_{NL} \approx L_{eff}$.

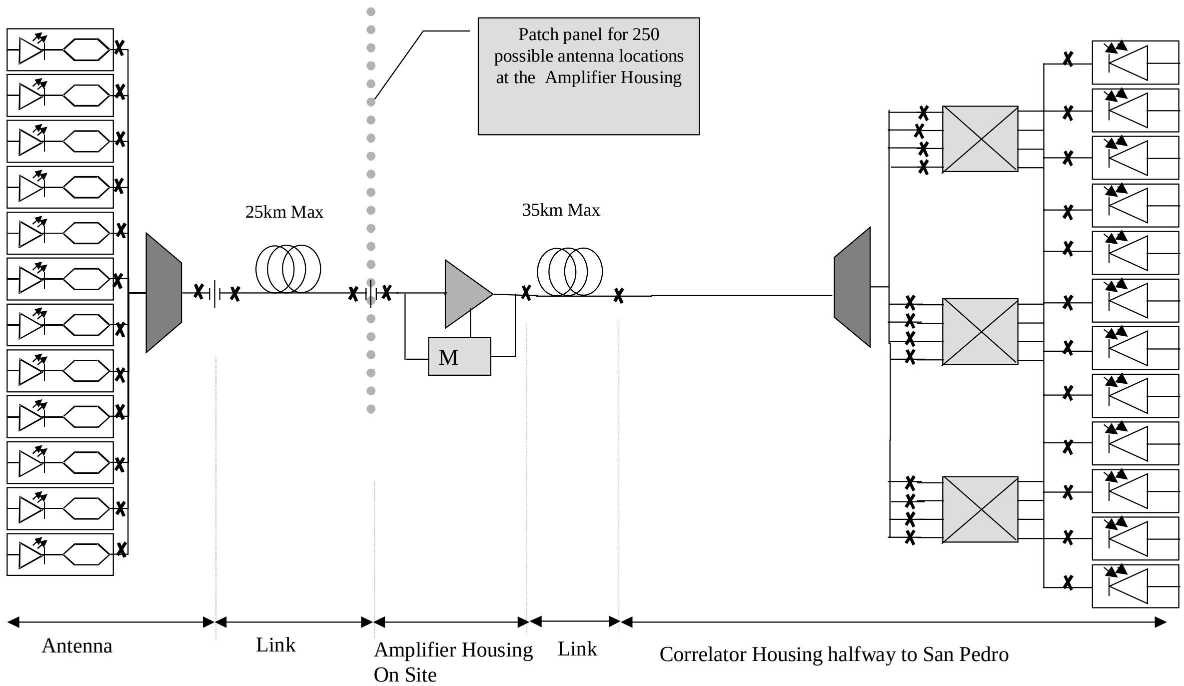
Substituting L_{eff} for L_{NL} in equation 2.7.5 we can see that for an effective Length of 15km the threshold power is 25.7mW.
Power penalty due to SPM over the link is considered negligible.

APPENDIX I

Alternative link design – Correlator Housed halfway between the site and San Pedro

Fig I.1 shows an alternative design strategy. Here we place the correlator housing halfway between the antenna site and San Pedro resulting in a 60km max link length.

Fig I.1 Proposed Design for the link halfway to San Pedro



The power budget below shows that this link design is possible using only one amplifier. Since there is not a great margin left in the power budget this strategy requires further, practical investigation to ensure it is a robust design which could be practically implemented.

Network Elements	Fibre distance km	Loss dB	distance dependant loss db
Laser Output (dBm)		0	
Splice		-0.1	
WDM combiner		-5.5	
Splice		-0.1	
Connector antenna to pad		-0.9	
Splice		-0.1	
array cable in trench 1 splice/2km	25	-7.5	0.3
Splice		-0.1	
Connector Link to patch panel		-0.9	
Splice		-0.1	
Input into amplifier		-15.3	
In Line Amplifier Output (dBm)		5	
Splice		-0.1	
Link to correlator 1 splice/2km	35	-10.5	0.3
Splice		-0.1	
WDM demux		-5.5	
Splice		-0.1	
Switch		-7.5	
Splice		-0.1	
Margin		-6	
Receiver Sensitivity		28	
Receiver Stage Power Budget		3.1	