ALMA Memo 463
Variation on the ALMA link design.
No Switch, maximum 18km link lengths and the use of an APD.

The link design of the ALMA data transfer system currently incorporates an erbium doped fibre amplifier, an optical cross bar switch and will operate over a system specified link length of 25km.
Over the course of the ALMA project the optical cross bar switch has been removed from the baseline plan and added to the contingency pool. In addition ongoing work on the Chajnantor site indicates that the maximum fibre link length will be 18km.
This document illustrates that the inclusion, or not, of an optical switch and the maximum link length specification are fundamental to the data transfer design.
It will discuss how the removal of the cross bar switch and reduced link length will eliminate the erbium doped fibre amplifier from the link design.

We show that a variant design using an avalanche photodiode, without an erbium doped fibre amplifier, will operate at the required performance levels. However, whilst the design includes a 6dB start of life margin, there is no additional margin over and above this level. The design is successful, only within strict limits of attenuation outlined in the power budget. Until the fibre optic cable is installed from the antenna pads to the AOS, a degree of uncertainty exists in the attenuation figures of the power budget. Additional attenuation cannot be accommodated in this design, without the use of additional amplification, or a sacrifice of system margin.
The existing design, incorporating an erbium doped fibre amplifier has additional margin over and above the 6dB start of life margin and will work with the inclusion of an optical switch and longer link lengths.

We conclude that, in order to ensure the data transmission system will operate under all foreseeable circumstances; the design should include an erbium doped fibre amplifier. The erbium doped fibre amplifier represents an estimated component cost of $640k to the project. Whilst costly, it permits maximum flexibility in the design. If practical, the design should be reviewed again, once the fibre cable has been laid at site and a firm decision about the optical cross bar switch has been taken, to ascertain if an optical amplifier is still necessary.
It is likely, however, that by this point the hardware designs will be fixed and the erbium doped fibre amplifier will remain by default.

System Description of the variant design

The ALMA data transmission system (DTS) will transfer data from each of the 64 antennas on site to a central correlator. This design is a variation on the ‘baseline’ design[1] data transfer system it assumes that both the antenna and correlator locations are at the Chajnantor plateau and that the maximum distance between the two will be 18km.
This is a reduction in the baseline specification that is, 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[2] 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 to 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.

Figure 1 illustrates the proposed link design.
Each fibre link from antenna to the 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 SMF optical fibre[2]. At the input of the correlator a DWDM demultiplexer will feed 12 avalanche photodiodes.

In the baseline design an erbium doped fibre amplifier (EDFA), at the correlator is 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.
Currently the optical switch is part of the contingency plan.

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 a link of 18km max length and no optical switch

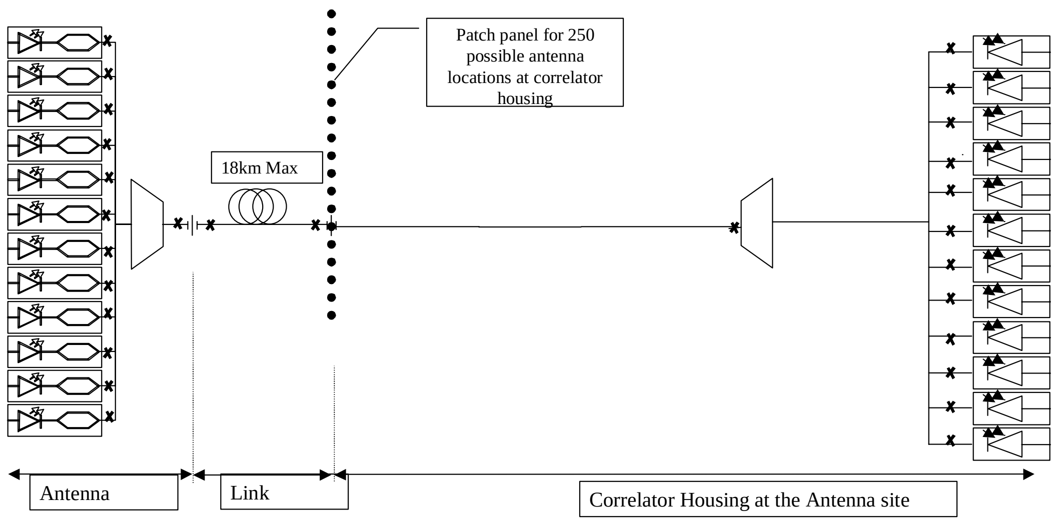

Fig1. Proposed design using an avalanche photodiode.

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 2 shows the total system attenuation, based on estimated values for the various system components. A 6dB start of life margin has been added to the power budget to accommodate component degradation over time.

Network Elements	Fibre distance km	Loss dB	distance dependant loss db
Laser Output (dBm)		0	
Splice		-0.1	
connector		-0.1	
WDM combiner		-4.5	
splice @ top of antenna		-0.1	
splice @ base of antenna		-0.1	
harsh environment connector		-0.1	
splice cable to connector		-0.1	
array cable in trench 1 splice/2km	18	-5.4	0.3
Splice outdoor to indoor cable		-0.1	
Splice to connector		-0.1	
Patch panel		-0.3	
Splice to routing cable		-0.1	
splice to connector		-0.1	
connector		-0.1	
WDM demux		-5.5	
Splice to routing cable		-0.1	
Splice to connector		-0.1	
connector @ receiver		-0.1	
MARGIN		-6	
Power Budget		-23.1	

Fig2. Power budget for variant design

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
$\lambda = 1.55\mu m$
L = Link length ; 18km
$c = 3x\ 10^8$ m/s

D = 17ps/nm.km for SMF fibre

When L = 18km $\in$ = 0.197 for SMF, 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:

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

$\Delta\tau$ 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:

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

T is the time period of the pulses and is B^{-1} = 100ps
For good quality SMF D_{PMD} = 0.1ps/√km.
According to equation, for a 18km link $\Delta\tau$ = 0.4ps << 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 18km of SMF 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 not 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.
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. In this, variant design there are no high power components in the system and therefore non-linear effects will not occur
Non-Linear effects include:

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

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:

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

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 3 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 3. 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 this variant link design thermal noise and shot noise will be present at the avalanche photodiode. The design calculations have been completed using the Multiplex Inc RP192DL specification sheet.

The minimum received power P_{rec} for an avalanche photodiode in the presence of shot and thermal noise is given by the equation[4]:

$$P_{rec} = \frac{Q}{\mathcal{R}}\left(qF_A Q\Delta f + \frac{\sigma_T}{M} \right)$$

$\mathcal{R}$ is the responsivity of the receiver
Δf is the Bandwidth of the receiver = 8GHz @ the 3dB cutoff point
q is the electronic charge = 1.9 x 10^{-19}Coulombs
F_A is the excess noise factor for the APD and is 10 in the worst case
M is the multiplication factor for the APD = 10 at low input power
σ_T is the thermal noise and can be calculated from the equation

$$\sigma_T^2 = \frac{4K_B T}{R_L} F_n \Delta f$$

where K_B is boltzmans constant = 1.38 x 10^{-23}
T is temperature in Kelvin = 298K
R_L is the load resister and has a typical value of 50Ω
F_n is the amplifier noise figure and is related to the amplifier noise in the receiver front end design. Here we use a worst case figure of 3dB.
When Q=11, as calculated earlier P_{rec} = -22.6 dBm

Comparison with Fig2 shows that this receiver sensitivity is 0.5 dB short of the power budget. This is not a significant difference, given the inclusion, in the power budget of a 6dB start of life margin, worst case figures of attenuation for components and a conservative estimate of link attenuation.

If the link attenuation of the furthest pad is measured at less than 4.9dB and the optical switch removed from the design. The link can be constructed without an EDFA, using an avalanche photodiode.
However any additional attenuation cannot be accommodated in this design, without the use of additional amplification, or a sacrifice of system margin.

Cost implications

The EDFA is estimated to cost $10k per antenna for the component and assembly costs of the unit (not including man power costs). The price of the avalanche photodiode is not significantly above the cost of a pin diode from the same manufacturer. This means that this variant design would represent a cost saving of $640k in component costs alone.
Some of this cost advantage would be offset by the cost of modifications to the receiver board. This would be required in order to accommodate the avalanche photodiode which is slightly smaller and has a differential co-planar output.
In addition the avalanche photodiode typically requires a bias voltage of 20V, 4 times that of the pin diode. This rises to 40V maximum rating at end of life.
The feedback loop to maintain the correct bias is available from the supplier, but will necessitate a redesign of the board.

Conclusions
Assuming that the maximum fibre link length is 18km and an optical switch is not required in the ALMA DTS. We show that a variant design using an avalanche photodiode, without an EDFA, will operate at the required performance levels. However, whilst the design includes a 6dB start of life margin, there is no additional margin over and above this level. The design is successful, only within strict limits of attenuation outlined in the power budget. Until the fibre optic cable is installed from the antenna pads to the AOS, a degree of uncertainty exists in the attenuation figures of the power budget. Additional attenuation cannot be accommodated in this design, without the use of additional amplification, or a sacrifice of system margin.
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We conclude that, in order to ensure the data transmission system will operate under all foreseeable circumstances, the design should include an EDFA. Whilst costly, it permits maximum flexibility. If practical, the design should be reviewed again, once the fibre cable has been laid at site and a firm decision about the optical cross bar switch has been taken, to ascertain if an optical amplifier is still necessary. If the avalanche photodiode is adopted at this stage a redesign of the receiver board will be required.
It is likely, however, that by this point the hardware designs will be fixed and the EDFA will remain by default.

References

1. ALMA Memo 349, Roshene McCool, Jodrell Bank Observatory, University of Manchester, UK.
2. Digital Transmission System Signalling Protocol, Robert W. Freund, September 25, 2000 Draft.
3. Optical Networks – A practical perspective, Rajiv Ramaswami & Kumar N. Sivarajan, Morgan Kaufmann.
4. Fibre Optic Communication Systems 2nd Edition, Govind P. Agrawal, John Wiley & Sons
5. High Capacity Optical Transmission Explained, D.M. Spirit & M.J. O'Mahony, John Wiley & Sons
6. Optical Fibre Communications Systems, Leonid Kazovsky et al, Artech House publishers.
7. Optical Fiber Communications, Principles and Practice 2nd Edition, John M. Senior, Prentice Hall
8. Limitations on Lightwave Systems Imposed by Optical-Fiber Nonlinearities, Andrew R. Chraplyvy, Journal of Lightwave Technology, Vol8 No10, October 1990