



Memo 75

Signal Transport for the SKA

R. Spencer

04/06

Signal Transport for SKA

Ralph Spencer

EWG Signal Transport Task Force

Dec 2005, revised April 2006 – Exposure Copy

Summary

This white paper looks at the data and signal transport issues for SKA. It is clear that optical fibre technology has a number of advantages including high data rates, low loss and low cost. There are design issues for fibre links which need to be considered, and the use of COTS equipment on cost grounds will mean that certain compromises will have to be made. SKA is big, not only in collecting area but also in terms of the interconnections required and hence transmitter/receiver pairs. Currently the highest data rate systems (40 Gbps and above) are expensive, however the expectation is that costs will decrease, driven by the needs of the telecommunications industry. A cost model is developed here based on current costs of 10-Gbps equipment, though the expectation is that SKA will have higher data rates particularly in the inner array. The costs on this basis are high, and form a substantial fraction of the proposed budget, and even vastly exceed it. However it is expected that the rapid developments in this technology will lead to a reduction in the cost per bit per second over the next few years. A number of issues raised are already being addressed by the SKA international community, however the signal transport task force also needs to keep a close eye on device and system developments with an eye to cost reduction.

1 Introduction

Interconnection of the various elements in a large radio telescope is fundamental, particularly when aperture synthesis techniques are used requiring signals from all pairs of elements to be brought together for correlation. The large bandwidths required particularly at high frequencies will require many Gbps for high fidelity data transport. Meeting the cost requirements will present a challenge. All the concepts being considered for SKA require high data rate connection from individual antenna or feed elements to processing devices. Accumulation of signals is likely to occur on several scales, for example in the sequence: feed elements → beam formers → stations → correlators, many aspects of which depend on details of the antenna concept. It is therefore difficult to come up with a general design and cost model which covers all possibilities, however the reference design provides a suitable basis on which to make initial calculations. This white paper will look at various aspects of data transport, concentrating on fibre optic aspects, with the aim of identifying the most critical areas. This work follows on from last year's discussions and papers presented at the Penticton SKA meeting [1,2].

The next section looks at the arguments for using optical fibre, followed in section 3 by discussion of the design issues involved for multi- mode and single- mode fibre links, for the use of analogue or digital links, and for LO signal transfer. Section 4 contains a cost model based on the reference design, but with an extension to other concepts in the form of a table. Finally conclusions and suggestions for further work are drawn.

2 Why Optical Fibres?

The techniques to be used for interconnection depend on distance and more particularly bandwidth. The bandwidth required for SKA depends on the application, for example we might envisage 1 Gbps data rates per domain for multiple narrow bands at L band (i.e. several bands placed in the 1-2 GHz band), or several 10's Gbps if wide bands (GHz) are used at cm wavelengths as for ALMA [3], E-VLA [4] and e-MERLIN [5]. Connection can be via coaxial cable, radio links, free space optical links, or by optical fibre.

Some considerations include:

- Losses in coaxial cable are high at high frequencies. The baseline design calls for a bandwidth of 4 GHz at cm wavelengths, and losses in even high quality coaxial transmission line means that spans of more than a few 10's of metres become problematic. Equalisation is likely to be needed and dispersion effects may require careful calibration when beam forming over a wide band. Historically, the VLA overcame the connection problem by using expensive low loss waveguide. This is unlikely to be a practical solution for SKA unless a radical change in microwave technology occurs.
- Microwave free space links via line of sight or satellites are typically limited to <200 Mbps by licensing authorities due to multiple users in a crowded spectrum. There is also the concern of having RF transmitters within the array.
- Free space optical links have been developed for use where laying fibre is impractical, e.g. across a street in a city. Current commercial devices operate at 1 Gbps [6] and higher bandwidth systems may become available in future. Commercial costs are relatively high since they need to compare with cable laying costs in major thoroughfares, though simpler systems specifically for SKA may be less expensive.
- Optical fibres are now used extensively in telecommunications. The low loss (0.25 dB per km at 1550 nm optical wavelength, e.g. [7]), low cost (a few cents per m) and a well developed technology means that use of optical fibre is preferred for multi-Gigabit data transmission, even within an equipment rack. Fibres have Terabit capability, using multiple wavelength channels (WDM – wavelength division multiplexing). Current installed fibres use 10 Gbps components per channel on backbone networks. 40 Gbps systems are being introduced but are currently more expensive than 4x10 Gbps and dispersion effects are more severe. New 160 Gbps systems are being developed which may be relevant on the SKA timescale.

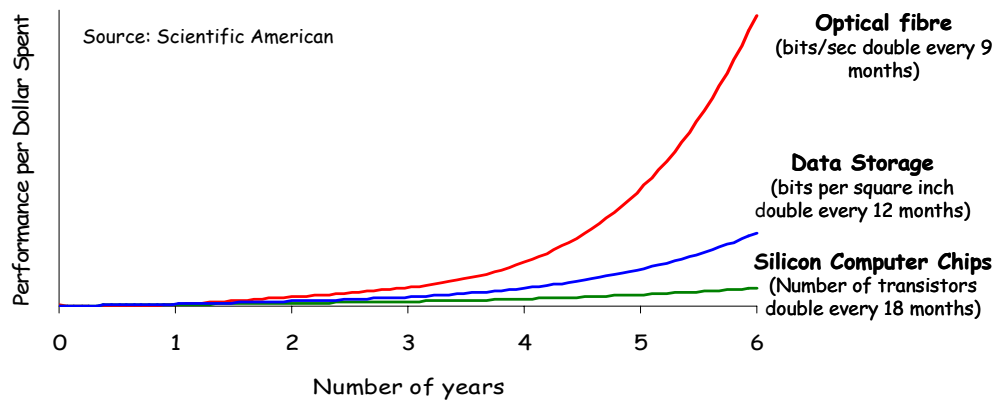


Figure 1. Performance per dollar prior to Jan 2001

For bandwidth and low loss optical fibre technology is the methodology of choice for interconnection in modern radio astronomy instruments – as emphasised in Roshene McCool’s review article [8]. Given that economics will dictate that COTS devices should be used whenever possible, the leading questions for SKA are therefore what fibre technology will give the data rates required when SKA is built and what will be the likely lowest cost? At the moment we can only extrapolate from what we know now. Figure 1 from a Scientific American article in 2001 [9] shows that we can perhaps be optimistic; the trend shown indicates that 25 Tbps devices will cost only a few \$100 by 2015 – however the graph was compiled before the dot-com crash and the introduction of inexpensive high capacity equipment has slowed somewhat since 2001 and such extrapolation is probably unrealistic. The article presciently pointed out the overcapacity of links compared with demand at the time. However a reasonable view is that 40-Gbps or 160-Gbps systems will be less expensive than today’s at 1 Gbps.

3 Design Considerations

Fibre optic technology can be broadly divided into two main areas: devices and systems using multi-mode fibre and those using single mode fibre.

3.1 Multi-Mode Fibre

Multi-mode systems are short range (< a few km) and relatively inexpensive. Local area networks commonly use this technology. Links operate at wavelengths from 600 to 900 nm and can use plastic fibre. Dispersion caused by the different mode paths through the fibre results in limits to fibre length and bandwidth. Many systems currently use 850 nm laser diodes on 62.5 μm core glass fibre with ranges of around 1 km for 1 Gbps Ethernet. Devices capable of 10 Gbps over ~ 0.5 km of 50 μm multi-mode fibre (mmf) have recently been announced [10]. An interesting development is the use of vertical cavity laser devices (VCSELs) that can be directly modulated and manufactured in arrays. It may also be possible to use inexpensive Light Emitting Diodes over short distances (10 m), as they are being developed for vehicle systems. These techniques may offer a solution to the high data rate problem for example in the Canadian Large Area Reflector design where the focal plane structure could have 2500 receivers each requiring Gbps data transmission from the aerostat down to the ground. VCSEL arrays containing 64 devices are available, and modulation rates of 10 Gbps have been used for short (300-m) links [11]. Quantum dot devices may also offer a cost-saving solution, and 10 Gbps operation has been shown to be possible [12]. There is every indication that high data rate and inexpensive systems should be available for SKA which will make heavy use of computer network technology for these short intra-station distances. SKA data rates are high compared with current practice, but use of the techniques to be available in future local area networks is attractive.

3.2 Single Mode Fibre

For path lengths greater than about 1 km and high data rates, it is necessary to use single-mode fibre (smf) in which the diameter of the fibre core is such that only one waveguide mode can propagate in order to get low loss and low dispersion. It is still possible to directly modulate the laser but the result is frequency chirp which limits the bandwidth and maximum range of current devices to sub 10 Gbps and sub 30 km. Improvements in the range and bandwidth of these devices are continually being made and it is possible for inexpensive long range (100 km plus) devices to be available in future. However, multiple fibres or wavelength division multiplexing techniques with wavelength-stable, externally-modulated devices will probably be required to reach Tbps rates.

The longer range and more expensive single mode systems generally operate in the 1300 or 1500 nm bands on 11 μm core glass fibre and can operate using externally modulated laser diodes over distances of up ~ 80 km without amplification at 10 Gbps. Fibres installed at the moment are limited to these two bands due to the strong absorption peak caused by the OH radical (figure 2), but some recent developments have eliminated this peak which could enable the whole 1300-1600 nm band to be available. The low loss 1550 nm band is generally used for long distance communications, but chromatic dispersion is higher in this band for standard fibre (figure 3). Dispersion compensation as well as amplification is required in links >100 km. Regeneration of the digital signal followed by re-transmission is required for links of more than around 300 km, e.g. in e-MERLIN at an intermediate site between the Cambridge telescope and Jodrell Bank. Note however that Marconi have announced [13] a long distance (3000 km) system using solitons which does not need regeneration.

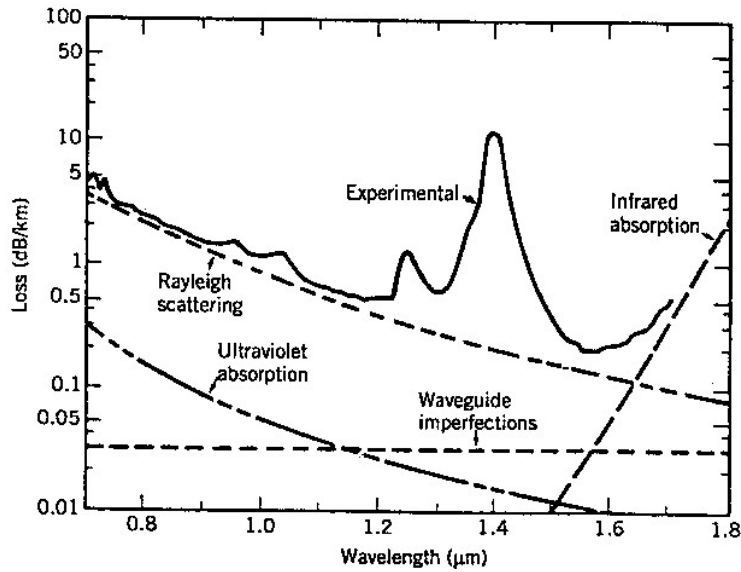


Figure 2. Attenuation in single mode fibre versus wavelength. The OH peak at 1.4 μm can be clearly seen, and most systems operate at around 1320 or 1550 nm (from [7]).

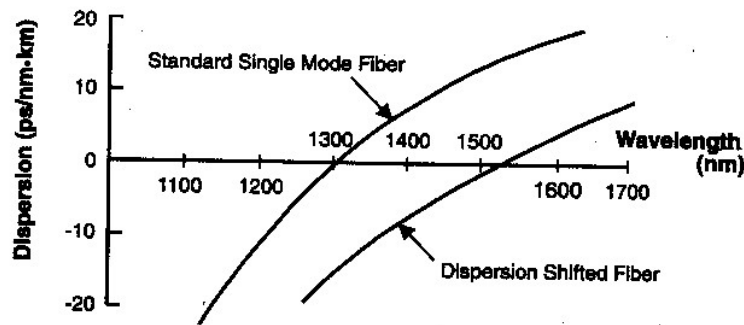


Figure 3. Dispersion versus wavelength. ‘Near zero’ dispersion shifted fibre is now often used in new links for use at 1550 nm (from [7]).

40 Gbps systems are being installed on some high capacity links using smf though dispersion is more of a problem, generally limiting link paths to <50 km before de-dispersion and amplification is required. Wavelength division multiplexing (WDM) allows multiple channels on one fibre. Fabry-Perot filters combine the light from a number of lasers onto one fibre. Coarse WDM uses wide separation between wavelengths and does not require high wavelength stability lasers. It is commonly used to provide multiple 2.5 Gbps channels on one fibre in current systems over spans of up to 80 km. Dense WDM (DWDM) has narrow channel separation: down to 50 GHz in some systems. ALMA, EVLA and e-MERLIN use 200 GHz channel spacing. The wavelength stability of the laser diodes needs to be good – requiring temperature control of the lasers. Many commercial devices have built-in Peltier coolers and sophisticated current control. Up to ~100 channels can be directed down one conventional single fibre, so potentially a single fibre can have >4 Tbps capacity.

The configuration specification for SKA deduced from science requirements [14] suggests that the antennas should be distributed such that 20% of the collecting area is within 1 km, 50% within 5 km and 75% within 150 km, with a maximum baseline of at least 3000 km.

Interestingly enough, these distances roughly correspond to points where data transmission techniques change, multi-mode systems for the inner array <1 km, a combination of techniques for 1 – 5 km and single mode systems for >5 km and beyond. The costing model described later will use this distinction. We will also assume that the inner 5-km array will be able to use mmf, though the limit at the moment is around 5 GHz-km.

Any data transport design needs to consider the effects of noise levels on bit error rates. In addition other effects reduce the fidelity of the signal and hence increase errors. A convenient way of characterising this is via a power budget [15], where the effects are assigned a loss penalty. Photodiode detectors are usually characterised by an input level for a given error rate, for instance the 10 Gbps Multiplex PiN diodes used in e-MERLIN and ALMA have an input sensitivity of -19 dBm for an error rate of 10^{-10} , corresponding to a Q factor [14] of 6.4.

In order to satisfy the end of life bit error rate requirement an additional start of life margin (6 dB for ALMA) needs to be included in the design calculations to accommodate component degradation over time, as well as a margin for additional, or unforeseen loss within the links. The following points need to be considered:

1. A power budget, to establish link loss and predicted received power levels at the receiver
2. Assigned power penalties, to take into consideration a 6dB start of life margin and transmission impairments incurred on the link, such as:
 - Dispersion (chromatic and polarisation mode)
 - Polarisation dependent loss
 - Transmitter extinction ratio
 - Crosstalk
 - Non-linear effects
3. A Q factor calculation to predict the link bit error rate, taking into consideration noise at the optical receiver, such as:
 - Thermal noise
 - Shot noise
 - Amplified Spontaneous Emission Beat noise

Non-linear effects usually limit power levels per wavelength to less than 5 mW in standard single mode fibre. Most commercial transmitters run at around 1 mW or 0 dBm, and should be accepted as the norm, unless special fibre is available.

3.3 Summary of Distance –Bandwidth Issues

The way in which technologies change according to distance and bandwidth are summarised in table 1. Approximate costs for an optical transmitter including modulation (which could be either direct to the laser or LED or external) are also shown.

Table 1 Distance and Bandwidth of optical links

Distance	Data Rate	Technology	Approx. cost of light TX and modulator
km	Gbps		\$
0.01*	0.025 (1)	650-nm LED MMF in-car systems	10
0.3	10	850-nm VCSEL MMF	100
1	1	850-nm VCSEL MMF	100
30	<10	1310/1550-nm direct modulation DFB laser	600
100**	10	1550-nm externally modulated laser	1500
80**	40	1550-nm ext. mod. Laser	8000

* There are plans for up to 1 Gbps systems for real-time camera applications using resonant cavity LEDs

** Further distances can be reached if amplification and dispersion compensation are used.

There are large costs advantages to be gained if the distance-bandwidth performance of inexpensive multi-mode systems can be improved.

3.4 Analogue or Digital

Use of amplitude modulation of the optical signal is standard in optical fibre communications (though other techniques such as frequency modulation are possible), either via varying the diode current as in directly modulated lasers (this also changes the wavelength and hence causes ‘chirp’), or externally via electro-absorption or Mach-Zehnder modulators. Analogue modulation has been used commercially for some years in antenna remoting and for TV signals. It is also used in the GMRT in India and notably for SETI in the Allen Telescope Array. It is a convenient way of transporting signals over distances of up a few km, and may offer a good solution for the inner part of SKA. The advantages are mainly the avoidance of high speed digital devices near the antenna elements which could give rise to interference. The disadvantages are that delay path variations in the fibre (mainly caused by temperature variations) need to be compensated for, and non-linear effects give rise to cross and inter-modulation distortion. The latter limits the dynamic range of the electrical signals which can be accommodated; important in the presence of RFI. A study [16] in 2000 of data transport links in MERLIN and in EVN showed that digital links were a preferred option. ALMA, EVLA and e-MERLIN all use amplitude shift keying (ASK) digital links, with digitisation close to the front end, and digital links are necessary if sharing long distance telecommunication links as in e-VLBI. Digital phased array feeds such as 2-PAD in the European SKADS project envisage digitisation very early in the signal processing chain, whereas EMBRACE is planning on analogue beam forming, with digitisation following – thus reduces the number of A/D converters and links required. The experience gained by the ATA and NTD will be very helpful in coming to a design decision for SKA.

3.5 LO and Clock Distribution

If there is one technical requirement to be met which distinguishes interferometers from any other kind of instrument it is the need for coherence. The timescale for significant phase variations should be as long as is necessary to allow calibration via phase reference observations (typically 5-10 minutes) and preferably longer. While distribution of a coherent local oscillator or clock signal is not a major problem for short (~km) distances using buried cable for the frequencies envisaged for SKA (it is a problem for ALMA!), the long haul links in the intermediate (100 km) and ultra-long (1000 km) links require some thought. The effects of path variations on the clock phase needs to be measured and corrected, usually via comparing signals over the forward and return paths, and assuming reciprocity. MERLIN uses go-and-return radio links over ~200 km, and use of go-and-return signals on optical fibre is being investigated [17]. The EVLA will use amplitude modulated optical fibre links on two buried fibres where diurnal temperature variations are reduced [18]. Phase rates of 2.8 ps per hour are required for coherence at 40GHz over 22 km of fibre. The higher specification required for ALMA requires photonic LO transport [10]. It is hoped that the radio links will be replaced in e-MERLIN by a similar system to that of the EVLA although the problem here is that much of the fibre links are in open troughs alongside rail track and so are subjected to large temperature variations. Cost considerations (see later) may force SKA to also have fibre links suspended on poles rather than buried in the ground, and so will have similar problems to that of e-MERLIN. An investigation into possible correction schemes is being undertaken in the SKADS project.

An indication of the nature of the issues can be illustrated as follows. We assume a maximum link length of 200 km, as appropriate for the long baseline array. There and back signals will be required and the phase transfer needs to be such that the rms timing error is less than a few ps. For 1 ps rms jitter at 22 GHz:

$$\begin{aligned}\Delta\phi &= \omega\Delta t = 2 \times \pi \times 22 \times 10^9 \times 10^{-12} \\ &= 0.138 \text{ radians} \\ &= 7.9 \text{ degrees}\end{aligned}$$

1psec rms jitter gives 1% de-correlation D at 22 GHz, i.e.

$$\begin{aligned}D &= 1 - e^{-\Delta\phi^2/2} \\ &= 0.01\end{aligned}$$

The light travel time over 200 km down a glass fibre is $(1.5) \times 200/3 \times 10^8 = 1.0 \times 10^{-3}$ sec., assuming a refractive index for glass fibre of 1.5. Hence a change of 1 ps gives a $\Delta t/t$ of 1×10^{-9} , and corresponds to a change of fibre length of 0.2 mm. The typical temperature coefficient for fibre is $\sim 10^{-5}$, so a change of 1 degree C over 200 km produces a change in length of 2 m. A 1 ps jitter at a modulation frequency of 10 GHz corresponds to $\Delta\phi=3.6$ degrees in phase. Any measuring system has to be able to measure better than this and be able to cope with variations of over a factor of 10^5 in a day.

An additional consideration is that birefringence in optical fibres causes polarisation mode dispersion (PMD), where different polarisations have different paths and arrive at different times (figure 4). Variations in temperature and vibration cause the paths to change on short timescales, so that the resultant signal at the output varies in the time of arrival. This causes jitter in communications signals, and installed telecommunication links have upper limits set on their PMD performance of typically a few ps. The rapid change in path length means that fibres are non-reciprocal, i.e round-trip phase measurements even on a single fibre are subject to uncompensated PMD effects. However careful control of temperature variations, use of high quality fibre and modern installation techniques allow round trip phase compensation to work even at the mm-wavelengths used for ALMA over ~10

km. Use of a pair of fibres within the same bundle as in the e-VLA and the ATCA has also been shown to work adequately for sub cm-wavelength radio astronomy for baselines of up to 15 km. As mentioned previously tests over the longer links used in MERLIN are envisaged as part of the SKADS project.

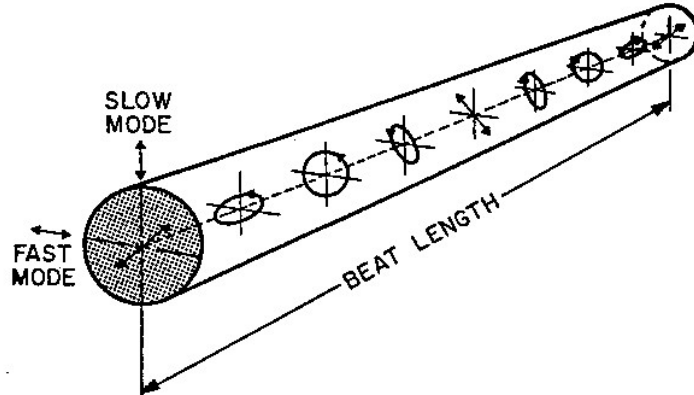


Figure 4. Polarisation mode dispersion in optical fibre. The net polarisation changes down the fibre, with the degree of birefringence being dependent on strain in the fibre e.g. caused by bending. The net effect is similar to a random walk and is $\approx \sqrt{(\text{length of the fibre})}$. Typical fibres have PMD coefficients of around 0.5 ps per root km, though they can vary considerably from one fibre to another.

4 Cost Model

In order to concentrate thoughts we will start with the reference design, i.e. an array of dishes of 12-15 m diameter, each fitted with a smart feed which is either a phased array feed having multiple elements N_e and producing a number of simultaneous beams N_b ($N_b < N_e$), or a focal plane array which has one element (a horn?) per beam. A cost model has also been developed for the SD-FPA design (see the white paper on the EWG web pages).

Data transport is divided up into 3 regions corresponding to the inner array, the long baseline array and the very long baseline array: short haul links of < 5 km, long haul of 5 to 150 km and very long haul of 150 to 3000 km.

We will assume a bit rate of 10 Gbps per device as currently available. Following current practice in EVLA, ALMA and e-MERLIN, this corresponds to a signal data rate of 8 Gbps after removing the overhead due to formatting and encoding, and hence a bandwidth varying from 0.5 GHz if 8 bit encoded to 2 GHz if 2 bits are used (one polarisation). The science requirements suggest a bandwidth of 8 GHz in each of two polarisations (each split into 2 IFs), hence the data rate per beam in the inner array could become $2 \times 8 \times 2 \times 10 = 320$ Gbps if full 8 bit accuracy is required with full bandwidth and including 8/10 bit encoding. As pointed out in [2], present day costs for such a link system with many beams will exceed the total \$1B budget for the whole of SKA (also see the table below). However the trend shown in section 2 above suggests that high data rate device costs may be comparable or even cheaper than today's 10 Gbps devices. The cost calculations here will assume a total data rate of 10 Gbps (both polarisations) since the capability in a few years is likely to be much higher for the same cost, and will perhaps achieve the 320 Gbps requirement.

We will set parameters as follows. The calculations are on a MathCad script which can be supplied if requested. The text below follows the script, but with more description and explanation. Multiple letters are used as variable names, avoiding subscripts which have other meanings in MathCad.

Initial parameter values are given in the text below, but other values and their effects are shown in a table later. Cost units are in dollars and distances in km.

Firstly the distribution of collecting area in SKA as defined by the science requirements. ‘Antennas’ here could mean small dishes, aperture array tiles, or large antennas.

Fraction of antennas within the central 5 km FS := 0.5

Fraction between 5 and 150 km (no repeaters) FL := 0.25

Fraction beyond 150 km (with repeaters) FVL := 0.25

We need to quantify the costs of laying fibre cables. It is interesting to note that that the costs for trenching cable for ALMA are estimated to be about \$50 per m. Costs in the UK are similar, at around \$45 per m in rural areas. The trenching costs dominate the total costs of the ALMA fibre network (an estimated \$6.5M out of \$7.4M). Power and communication cables also need to be laid, so these costs could be part of the infrastructure. However costs are high, particularly for the long baseline arrays and therefore are included here, particularly since the distance involved depends on the configuration. The costs are also likely to be different for open country versus additional costs of laying fibre at the same time as road construction takes place. Furthermore power has to be distributed within a station, along with other communication signals, and so data transport costs should be folded in with these. However a full cost estimate of the civil work required is beyond the scope of this report, and so indicative figures are used.

Since the site chosen for SKA is likely to be a friendlier environment than the Atacama desert, and be more open country than in the UK, we will assume a cost of \$10 per m. or F=10000 \$ per km, (but see comment in section 4.4).

4.1 Short Haul Links (< 5km)

Here we assume that the range of inexpensive devices will be extended from the present day 0.5 km to 5 km in a few years time. Today’s single mode systems using directly modulated laser diodes will certainly work over this distance, but they are more expensive than multi-mode devices.

Number of beams $N_b = 40$. These are formed at the individual antenna, e.g. via an FPA, or by subsequent processing. We need to distinguish the two cases.

Assuming for the moment that there is one 10 Gbps channel per antenna, the cost of transmitter and drivers (a current 10 Gbps VCSEL (mmf) is \$60) $T_s = \$100$.

Cost of receiver and electronics $R_s = \$100$.

The number of antennas required very much depends on the concept. Assuming the LNSD design the total number depends on size, e.g. ~8000 for 12-m diameter dishes $N_a = 8000$

Average distance (km) between antennas and correlator $L_s = 2$ km

This assumes that the beams from each antenna are brought back to a central processing centre. The true number here will depend on the configuration and be smaller if the antennas are concentrated in the centre of the array.

4.1.1 Beam former at the focus

The cost per antenna, assuming beam former is at the focus (either FPA or digital PAF) and number of fibres = number of beams (as would be required for multi-mode fibre, where optical multiplexing is not yet possible).

$$Ca1 := 0.05 \cdot F + N_b \cdot (T_s + R_s)$$

$$Ca1 = 8.5 \times 10^3 \quad \$$$

Trenching costs for a 50-m connection from the antenna feed to base equipment has been assumed. Total cost for short haul links C_s is therefore given by the product of the number of antennas and the total link plus trenching costs:

$$C_s := FS \cdot Na \cdot (Ls \cdot F + Ca1)$$

$$C_s = 1.14 \times 10^8 \quad \$$$

Note that sharing trenching in a tree structure for the fibre interconnects will save costs here.

4.1.2 Beam former away from the focus

If the beams are formed away from the focus, then each antenna element, e.g. in a phase array feed, needs to be connected down to the beam former. Further optical transmitter/receiver pairs are then needed to transport signals to the correlator.

Number of elements in the phased array feed e.g. $Ne = 100$ and cost per antenna becomes

$$Ca2 := 0.05F + Ne \cdot (Ts + Rs)$$

$$Ca2 = 2.05 \times 10^4 \quad \$$$

giving total cost of the inner array of

$$C_s := FS \cdot Na \cdot [Ls \cdot F + Ca2 + Nb \cdot (Ts + Rs)]$$

$$C_s = 1.94 \times 10^8 \quad \$$$

This is almost double the cost of beam forming at the focus. Note also that if the links need to be duplicated for higher bandwidth then we could expect a very much higher cost.

4.2 Long Haul (5-150 km)

We assume antennas are aggregated into stations, and N_{bl} beams are formed. This may be different to the number of beams in the inner array and so has a different variable name. Number of beams per station $N_{bl} = 40$.

If the distribution of collecting area is organised into stations to save interconnections, then each station produces N_{bl} signals to be connected back to the central processor. The total number of stations excluding inner array is e.g. $N_s = 100$ with an average distance between stations and processor of $LL = 40$ km. Note that N_s includes the very long baseline array i.e. N_s is the total number of stations in SKA, excluding the inner array.

Trenching costs will be high here so to be realistic a configuration needs to be considered. Let's assume that the configuration is in the form of a multi-arm spiral. Dig costs could be reduced since the telescopes could be connected in series. Suppose there are $m_l = 5$ spirals

Then the total length of fibre is $L_t := 1.48 \cdot 150 \cdot m_l$
km

The factor of 1.48 comes from integrating the path length over a $r \sim \theta^2$ spiral, θ extending from 0 to π .

If all the short link beams are aggregated within a station, then link cost is on a similar basis to the short links above. The number of antennas in a station is

$$N_{as} := (FL + FVL) \cdot \frac{N_a}{N_s}$$

$$N_{as} = 40$$

Assume that all antennas are within 100m, so we can use the inner array calculation for the antenna costs. Choosing $Ca1$ for the antenna costs, then the cost of a station $C_{st} := N_{as} \cdot Ca1$

$$C_{st} = 3.4 \times 10^5 \quad \$$$

The cost of long haul transmitter and electronics will be higher here, current costs are around \$1500 for a 1/2 transponder transmitter suitable for DWDM equipment, including digital electronics this becomes $Tl = \$2000$. The receiver plus electronic costs are $Rl = \$1000$. DWDM techniques will be used so optical multiplexers and de-multiplexers will be needed.

The cost of a multiplexer or a de-multiplexer (depends on the number of wavelengths= N_{bl}) is approximately $M = \$2000$. One of each is required per link.

The cost of the long links becomes:

$$Cl := \left[\left(\frac{FL}{FL + FVL} \right) \cdot N_s \cdot [C_{st} + N_{bl} \cdot (Tl + Rl) + 2 \cdot M] \right] + Lt \cdot F$$

$$Cl = 3.43 \times 10^7 \quad \$$$

Note that the fraction of stations in the 150 km array is $FL/(FL+FVL)$ if N_s is the total number of stations excluding inner array.

4.3 Very Long Haul Links (150-3000 km)

This calculation will assume that the necessary interconnection will be made by the SKA project. This is probably unrealistic as it makes sense to use existing fibre networks where available. Costs for leasing bandwidth over such links is falling rapidly, and so may become a viable option (see discussion later).

These long links will need repeaters, where signals are amplified and de-dispersed. Cost of de-dispersion, amplifiers and regeneration per repeater is likely to be $Cre = \$5000$

Distance between repeaters $LR = 80$ km.

The costs since now dominated by fibre trenching will be largely determined by the configuration. Suppose we have a 3-armed spiral with the correlator at the middle, then the total length of the links becomes $Lvt := 1.48 \cdot 3000 \cdot 3$ km, using the factor of 1.48 as before.

Cost of the fibre connection is then

$$C := Lvt \cdot F$$

$$C = 1.332 \times 10^8 \quad \$$$

The cost of leasing fibre needs to be compared with this figure. The total link costs for the very long baseline links becomes

$$C_{vl} := \left(\frac{FVL}{FL + FVL} \right) \cdot N_s \cdot \left[C_{st} + N_{bl} \cdot (Tl + Rl) + 2M + \frac{LVL}{LR} \cdot C_{re} \right] + L_{vt} \cdot F$$

$$C_{vl} = 1.595 \times 10^8 \quad \$$$

The difference between C and C_{vl} above shows that the opto-electronics forms only a fraction of the total costs of the links, even when the total number of beams for the distant array is N_{bl}=40.

The total costs on the above basis becomes:

$$\text{Total} := C_s + C_l + C_{vl}$$

$$\text{Total} = 3.878 \times 10^8$$

Excluding the very long links:

$$C_s + C_l = 2.283 \times 10^8 \quad \$$$

This is already a substantial fraction of the total budget, before we consider the effect of the full data rate (only 10 Gbps per beam assumed here).

4.4 Other Values for Parameters

Table 2 below summarises the results of the model. Column 2 repeats the numbers shown above. Column 3 labelled 'reference 1' shows the same parameters except that the number of beams used on the longer arrays (5-150 km and >150 km) is put to unity. Column 4 shows the effect of increasing bandwidth to 320 Gbps (i.e. 8 GHz per polarisation, 8 bits, 2 polarisations) on the whole array, using present technology and assuming that the bandwidth is achieved by having 32x10 Gbps channels. Only one beam is assumed for the outer array, and that the repeater costs are similar (since multiplexers with 32 channels are available now). Column 5 shows values where large single antennas are used. The number of elements in a focal plane array required is large in order to get the field of view required, but there is only one antenna to consider per station. Column 6 shows that calculation for an aperture tile array, where the tiles are assumed to be organised into individual beam forming arrays of 100 m² and hence 10000 individual arrays are required. Note that 40 beams have been assumed for the reference design. Increasing the number of beams on the small array to 100 increases the small array cost to \$1.62.10⁸ for the FPA design and the total to \$4.72.10⁸ for 1 beam in the outer array (compare with column 3).

Recent discussions on the reference design suggest that 10-m dishes may be used, requiring ~10000 antennas. Also fibre trenching costs in open country in Australia may be as low as \$3 per m, Using these figures in the costing program (column 7) results in a small reduction in the short and long link costs and a large (2.5 x) reduction in the very long links compared with the figures in column 2. This is mainly due to the decrease in trenching costs, in spite of the increase in the number of antennas.

Table 2 Summary of Costs:

Parameter	Reference	Reference 1	High band width	LAR/FAST	Aperture Tile	Reference*
Column 1	2	3	4	5	6	7
Short Links						
Beams Nb	40	40	40	2500	100	40
Tx Ts \$	100	100	3200	100	100	100
Rx Rs \$	100	100	3200	100	100	100
Antennas Na	8000	8000	8000	1	10000	10000
Av dist. Ls km	2	2	2	0	2	2
Ant. Con. costs Ca1 \$	$8.5 \cdot 10^3$	$8.5 \cdot 10^3$	$2.57 \cdot 10^5$	$5.0 \cdot 10^4$	$2.06 \cdot 10^4$	$8.2 \cdot 10^3$
Small array costs Cs \$	$1.14 \cdot 10^8$	$1.14 \cdot 10^8$	$1.11 \cdot 10^9$	$5.0 \cdot 10^4$	$2.0 \cdot 10^8$	$7.1 \cdot 10^7$
PAF, no. of elements Ne	100	100	100	2500	100	100
Ant. Costs Ca2 \$	$2.05 \cdot 10^4$	$2.05 \cdot 10^4$	$6.4 \cdot 10^5$	$5.0 \cdot 10^5$	$2.05 \cdot 10^4$	$2.05 \cdot 10^4$
PAF small array costs Cs	$1.94 \cdot 10^8$	$1.94 \cdot 10^8$	$3.67 \cdot 10^9$	$1.0 \cdot 10^6$	$3.03 \cdot 10^8$	$1.94 \cdot 10^8$
Long Links						
Beams Nbl	40	1	1	1	1	40
No. of stations Nas	100	100	100	20	100	100
No. of antennas per station	40	40	40	1	50	50
Cost per station Cst \$	$3.4 \cdot 10^5$	$3.4 \cdot 10^5$	$3.4 \cdot 10^5$	$3.4 \cdot 10^5$	$1.03 \cdot 10^6$	$4.1 \cdot 10^5$
Tx Tl \$	2000	2000	64000	2000	2000	2000
Rx Rl \$	1000	1000	32000	1000	1000	1000
Mux costs M \$	2000	2000	2000	2000	2000	2000
Cost of long links Cl	$3.43 \cdot 10^7$	$2.85 \cdot 10^7$	$5.29 \cdot 10^8$	$2.13 \cdot 10^7$	$6.27 \cdot 10^7$	$2.4 \cdot 10^7$
Very Long Links						
Cost of repeater Cre \$	5000	5000	5000	5000	5000	5000
Repeater spacing LR km	80	80	80	80	80	80
Cost of v. long links Cvl \$	$1.60 \cdot 10^8$	$1.54 \cdot 10^8$	$6.54 \cdot 10^8$	$1.45 \cdot 10^8$	$1.88 \cdot 10^8$	$6.4 \cdot 10^7$
Total \$	$3.88 \cdot 10^8$	$2.22 \cdot 10^8$	$4.85 \cdot 10^9$	$1.66 \cdot 10^8$	$7.03 \cdot 10^8$	$2.6 \cdot 10^8$

4.5 Discussion

It is very clear that the link costs using present day technology are prohibitively high, particularly if full bandwidth is needed over the whole array. New technology may solve the bandwidth problem, though the interconnection costs are likely to remain high. Some saving will be possible in the inner array by trench sharing in a tree structure to figures nearer those estimated for ALMA, i.e. to around a few \$M. The splicing and connectorisation required remains a formidable work programme for the LNSD design.

Reducing the number of beams reduces the device count and hence also reduces cost. However having only one beam in the 150-km array surprisingly reduces costs by only 17%, and by only 3% in the very long baseline array (comparing columns 1 and 2). This is because trenching costs dominate here. To some extent there is a trade off between beams and bandwidth. Considering only one beam but with 320 Gbps data rates, the link cost of the small array using a phased array feeds with beam forming away from the focal plane is about 30% less than shown in column 4, the long haul links are around a factor of 20 less and the very long links are around 4 times less, resulting in an overall figure of \$2.8.10⁹, a factor 2 less than the figure in column 4.

The use of large telescopes reduces the costs considerably – as the telescope is doing most of the combining of the radio astronomy signals rather than via data distribution and electronic beam forming.

Link costs for the tiles is also high – however the bandwidth here is not likely to exceed 10 Gbps per element (assuming 8 bit digitisation) since it is a low frequency array. Any hybrid concept will share trenching of course, and to some extent could share links, though this will depend on detailed design.

It is clear that provision by SKA of full bandwidth connections to the stations in the very long baseline array is expensive. The ideal would be a dark fibre connection, perhaps as part of a strategic fibre interconnection between major sites. Another approach might be to use existing internet connections (though the ‘last mile problem’ will exist requiring the station to be connected to the nearest network point of presence). Here the current experiments in e-VLBI are relevant. Data rates of 512 Mbps have been achieved with Europe and across the Atlantic using 1 Gig Ethernet equipment. Data rates are limited by end host performance and by small levels of packet loss lowering TCP rates. There are plans to connect the Onsala telescope to the e-MERLIN correlator at 4 Gbps using either 10 GE or multiple 1 GE cards in the EU’s EXPRoS project. Networks are moving to light path capability where dedicated and deterministic interconnects are set up for high bandwidth applications. In the future we expect that all-optical networks will enable multi-Gbps or even multi-10 Gbps interconnection (see paper by Khoe and van den Boom [19] for discussion of this in the SKA context). So the problem for SKA becomes more one of the leasing costs of such capability on the commercial and research links of the future.

The results shown here indicate that a cost reduction programme is necessary. This is likely to involve a compromise between baseline length, bandwidth, field of view and number of beams. A trade off where the more distant stations have lower numbers of beams and lower data rates may be necessary. One way of decreasing data rates is if the longer baselines make use of fewer digitisation bits, since interference tends to be local and VLBI is known to work in the presence of strong interference even with only 1 or 2 bit digitisation.

5 Conclusions and Further Work

Fibre optics will play an important role in signal transport for SKA, not only for high bandwidth radio astronomy data transfer, but also in local oscillator distribution and control and monitoring. There is however a number of issues which will need to be clarified before design of such systems can begin.

1. The costs of laying fibre cable in the ground on current technology are high, and may even dominate the signal transfer budget. Alternative and cheaper alternatives should be investigated, preferably in collaboration with site working groups and civil engineers. For instance it may be possible to lay armoured cables on open ground, or suspended on poles, though temperature variation may be too high for the LO stability required.
2. The use of analogue links to a central laboratory lab may be a viable option for the compact array. The experience of the US Allen Telescope Array, and the Australian NTD project will be useful in considering design options for SKA.
3. Further work on coherent signal transfer over fibre spans of up to 150 km (or perhaps even 1000’s km) needs to be done. The work proposed for SKADS, and the experience obtained by the EVLA will be helpful here.
4. The way in which the individual elements are connected matters. Outline configurations are needed to enable the length dig to be minimised.
5. Bandwidth and beams cost. As the capabilities of low cost devices increase then the capabilities of SKA for a given cost increase. Cost considerations may impact on the bandwidth and number of bits to be used for digitisation, and compromises on the scientific requirements may have to be made. A close eye should be kept on the availability of devices, and given that the telecommunications industry will drive development forward, then design decisions on the technology and devices to be used should not be made until as late as possible. How the field of view should vary with resolution offers a way out, this effects computing requirements as well. A study of the impact such changes would make on the science should be undertaken.

6. One should not dismiss the possibility of all optical systems where even the processing is done optically. A number of recent developments, mostly for all-optical networks, have shown that the need for critical high speed electronics can be reduced, and it may even become possible for correlation and beam forming to be done optically.

The cost model developed in this paper is admittedly fairly crude, but it does outline the issues. More work is required on the model is required, particularly on the trenching costs for the various configurations being considered and in considering the trade off between number of beams and field of view. More detailed designs can be made when specific configurations and design parameters are known.

Acknowledgements

Thanks are due to Ron Beresford for pointing out the availability of inexpensive 10 Gbps VCSELS, and Ed Ackerman, Peter Clarke and Andrew Faulkner for valuable comments on the manuscript.

References

- [1] Maat, D.H.P. and Kant, G. W., *Fiber Optic Network Technology for Distributed Long Baseline Radio Telescopes*, EXPA 17, 213, 2004.
- [2] Spencer, R., McCool, R., Anderson, B., Brown, D, and Bentley, M., *ALMA and e-MERLIN Data Transmission: Lessons for SKA*, EXPA 17, 221, 2004.
- [3] <http://www.nrao.edu/almamirror/> *The Atacama Large mm-wave Array*
- [4] <http://www.aoc.nrao.edu/evla/> *The VLA Expansion Project*
- [5] <http://www.jb.man.ac.uk/e-merlin/> *e-MERLIN Science Case and Technical Specification*
- [6] <http://www.cablefreesolutions.com>, <http://www.pavdata.com> Companies supplying free-space systems
- [7] Senior, J. M., *Optical Fibre Communications, Principles and Practice*, 2nd ed. Prentice Hall, 1992.
- [8] McCool, R., et al. *Enhancing the sensitivity of radio telescopes using fibre optic networks*, URSI Review, in press
- [9] Stix, Gary, *The Triumph of Light*, Scientific American, January 2001.
- [10] <http://www.advancedopticalcomponents.com> High speed VCSEL devices.
- [11] Michalzik, R., et al., IEICE Trans. Electron. E84-C, 629, 2001.
- [12] Markus, A. and Fiore, A., Phys. Stat. Sol. (a), 201, 338, 2004.
- [13] <http://www.marconi.com/Home/Search;internal&action=search.action> Papers on solitons and 160 Gbps links.
- [14] Jones, D. L., SKA Memo 45, available at http://www.skatelescope.org/pages/page_skares.htm SKA technical requirements
- [15] Agrawal, G. P., *Fibre Optic Communication Systems*, 2nd Edition, Wiley, New York 2002.
- [16] Smith, B. et al. *Optical Fibre Communications Between Radio Telescopes in the European VLBI Network*, TMR-LSF RTD Sub Project 4, under EU contract ERB FMGEXT 980101, 2000.
- [17] Strong, M., PhD Thesis, The University of Manchester, 2005
- [18] Durand, S. and Cotter, T., *Operational Performance of the EVLA LO Round-trip Phase System*, Proc. SPIE Int. Soc. Opt. Eng. 4845, 63, 2002.
- [19] Khoe, D., van den Boom, H., *Trends in Electro-Optical Communication Systems*, in Perspectives on Radio Astronomy: Technologies for Large Antenna Arrays, eds. A. B. Smoulders and M. P. van Haarlem, ASTRON, Dwingeloo, 1999.