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A Clock for the Square Kilometre Array

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The Square Kilometre Array telescope will be the largest and most complex astronomical instrument to date, with individual antennas spread across continental scales. One of the most complex technical challenges of such an extended array is the coherent combination of astronomical signals collected independently by many remote antennas. Astronomical observations therefore must be time-stamped with clock signals of exquisite accuracy and precision. Traditionally, these signals were provided by separate atomic clocks installed at each telescope site, which are synchronised over long time scales via GPS. However, the scale of the SKA makes the cost of operating and maintaining such an ensemble of complex and expensive atomic clocks extremely difficult. The National Time and Frequency Network collaboration is developing a novel solution which turns the problem on its head. We plan to recycle the optical fibre network, used to transport the astronomical data to the Square Kilometre Array's central computer, to also distribute high-quality time and frequency signals to each antenna. We are developing and then amalgamating six techniques to enable a versatile timing and frequency network that spans continental scales. Our work brings together cutting edge technological innovations with astronomical science of the highest precision.

From Antikythera to the Square Kilometre Array: Lessons from the Ancients,
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[1] Speaker

1. Precision Timing in Radio Astronomy

The Square Kilometre Array (SKA) will be an interferometric radio telescope array with individual antennas spread across continental scales [1]. The astronomical data obtained by these antennas are transferred via an optical fibre network to a central processor, the correlator, which combines the data to form synthesised images. This real-time data transport network defines the SKA as a continental-sized, electronic very-long-baseline interferometry (e-VLBI) telescope array. However, the interferometry process only works if each antenna's data arrives at the correlator at the right time; that is, each data stream must be precisely synchronised in time [2]. Most interferometric telescope arrays achieve this synchronisation in multiple stages. First, the data streams are coarsely time-stamped with a global position system (GPS) signal to provide a time reference accurate to around 1 μs. Then, a 'fringe finder' source is observed enabling synchronisation of all antennas to within one cycle of the observation frequency. An atomic clock, co-located at each antenna, functions as a fly-wheel to track this frequency after the antennas are steered to the astronomical target. Any subsequent fine adjustment is conducted after data has been Fourier transformed by the correlator.

Natural temporal variations of the Earth's atmosphere (ionosphere and troposphere) above the antennas results in a steady decorrelation of the phase synchronisation between antennas. Much effort has been made to understand the temporal dynamics of the atmosphere (see for example [3]) with the aim of predicting its impact on the signal phase at each antenna. The application of an appropriate phase correction can therefore increase the length of time the array can operate before it has to be repositioned on the phase calibrator object. Another process which limits the coherence time of an interferometric array, and which is indistinguishable from atmospheric variations, is the relative drifts of each antenna's atomic clocks. Figure 1 demonstrates how a drift of one antenna's clock leads to decorrelation.

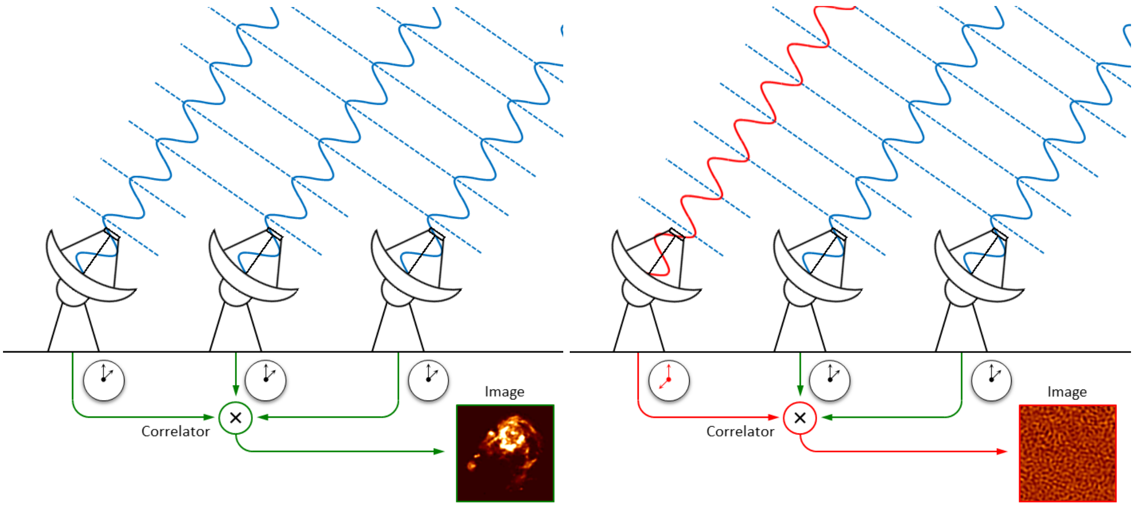

Figure 1: Left panel; interferometric array observing a coherent astronomical source with all clocks synchronised leading to an optimal correlator output. Right panel; a relative clock drift (shown in red) results in the inaccurate time-stamping of received data which thus washes-out the correlator output.

The relative importance of the atmosphere versus clock stability depends primarily on the observation frequency and the quality of the weather conditions [4]. In the case of the SKA, a rubidium atomic clock, which is relatively cheap, would lead to significantly greater impact than the ionosphere. However, the next best thing, a hydrogen-maser atomic clock is much more expensive and complex, and requires magnetic shielding, temperature-stabilised environments, and specialised maintenance if the unit develops a fault. On the other hand, the effect of clock drifts can be completely eliminated by connecting all antennas to one central master clock. As each antenna station in the SKA must necessarily be linked with high capacity optical fibre (required to transport the astronomical data to the central correlator) it is possible to recycle the same optical fibre network to send high quality time and frequency signals to each antenna.

In this paper, we explore an SKA that is centrally synchronised using its own optical fibre network. Specifically, we describe six techniques and technologies that are needed to realise this outcome. In doing so, we are effectively transforming the vision of the SKA from an e-VLBI array, into a continental-scale connected element interferometer.

2. Time and Frequency Dissemination via Optical Fibre

The transfer of timing signals across optical fibre [5] started in the mid-1990s with optical metrology researchers wising to access the ultra-stable signals from the state-of-the-art atomic clocks used in other experiments. However, the clocks may have been in the lab next door or even in a building across campus. The problem was that the stability of the atomic clocks had become so good, that standard dissemination schemes (radio or microwave links via satellites or cables) were no longer sufficiently stable to convey the full precision of the transmitted signal. Figure 1 shows the improvement of the stability of atomic clocks over a period of six decades.

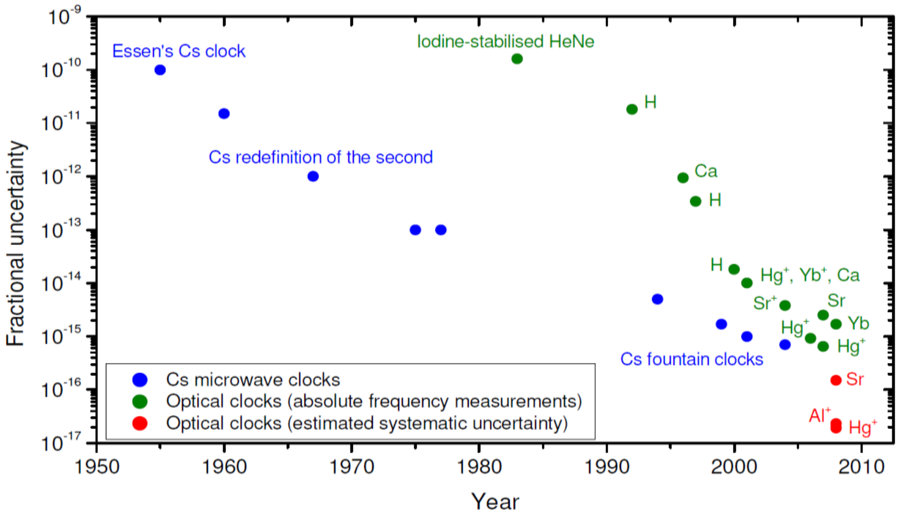

Figure 2: A plot showing the improvement of atomic clock stability (fractional uncertainly) from the date of the first microwave-frequency atomic clock in the mid-1950s to the present day (shown in blue). Optical-frequency atomic clocks, first demonstrated in the early-1980s (shown in green), can be seen to improve in stability at an even faster rate. Adapted from [6].

These researchers developed a technique to sense the optical path-length fluctuations of the optical fibre (arising from mechanical, acoustic, and temperature variations), using the very signal that they were interesting in transmitting. The output signal from this measurement is then used to cancel the effect of these noise sources, thereby resulting in a stabilised link with up to three orders-of-magnitude improvement in stability over the previous schemes.

The stabilisation of optical fibre has spread from the original implementation of cross-campus links, to links spanning hundreds of kilometres [7-9]. The current distance record for transferring an optical frequency on a stabilised link is 920 kilometres [10]. However, an optical frequency cannot be used for telescope synchronisation without down-converting the optical frequency to a radio frequency using a complex, high-cost optical frequency comb [11, 12]. Alternatively, radio frequency signals can be transferred directly, via modulation of the laser source [13, 14]. However, links utilising a modulation signal to sense the fibre fluctuations do not achieve the same level of stability as those using an optical frequency because of the lower resolution of radio (as compared to optical) frequencies. In addition, links transferring a modulation signal are generally only capable of attaining half the length of optical frequency links. This is because the modulation signal is attenuated at twice the rate of a single optical frequency, as the modulation signal is simply a product of two (or more) optical frequencies, each of which is being attenuated. Nonetheless, the electronic-Multi-Element Radio Linked Interferometer Network (e-MERLIN) radio telescope (see Figure 2) [15] has successfully implemented a radio-frequency modulation technique [16], and has thus become the first connected element interferometer with an extent greater than 100 km. However, this synchronisation technique cannot be scaled to apply to the size of the SKA. A more versatile system is needed which can meet all the requirements of the SKA.

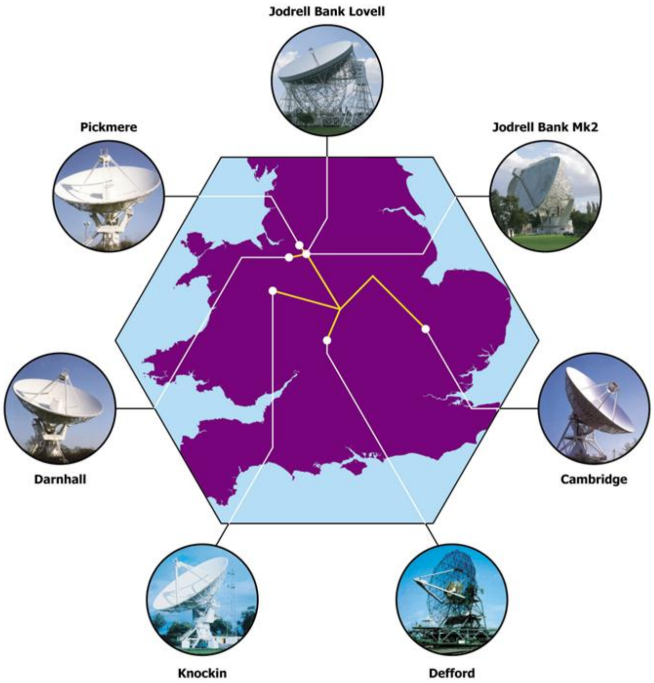

Figure 3: Schematic representation of the e-MERLIN radio telescope array indicating the locations of the individual antennas comprising the array and the optical fibre links connecting them to the central correlator and maser clock source [15].

3. The National Time and Frequency Network

The National Time and Frequency Network (NTFN) is a project to develop the techniques and technologies needed to simultaneously disseminate accurate time and frequency information via optical fibre across continental distances. These signals must be able to co-exist with conventional digital data transmitted on existing networks where required. Plans are in place to deploy the NTFN in Australia, beginning with the connection of five major cities as well as the radioastronomy facilities in central NSW. Although the techniques and technologies can be readily applied to equivalent systems elsewhere in the globe, Australia is in unique position compared to similar projects in North America and Europe. Australia’s dedicated research fibre infrastructure, operated by the Australia’s Academic and Research Network (AARNet, a key partner in the NTFN), includes unlit fibre over thousands of kilometres that can be used to test custom applications in a controlled field environment - an opportunity rarely existing in other countries. Access to this network avoids the issue of having to deal with multiple telecommunications providers across national boundaries, as is the case in North America and Europe. Figure 4 is a map of Australia highlighting the extent of the AARNet fibre network and indicating some of the potential users of the NTFN.

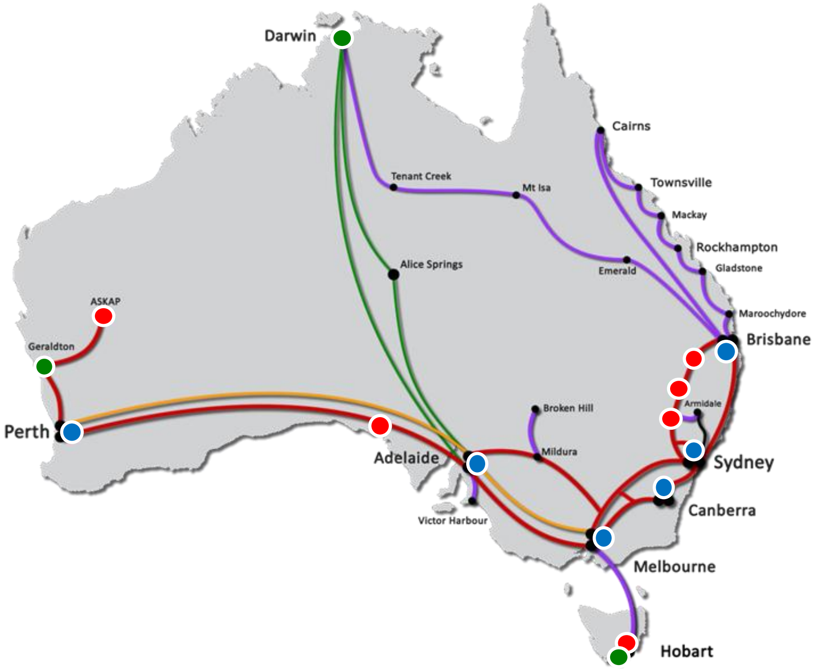

Figure 4. Map of Australia showing the extent of AARNet and CSIRO fibre links and the location of potential users of the NTFN distributed timing network: radio astronomy (red circles), fundamental physics (blue circles), geodesy (green circles), major population centres for advanced industries (black circles) [17].

4. Distributed Timing for the Square Kilometre Array

The time and frequency dissemination techniques and technologies currently being developed for the NTFN are ideally suited to support precision timing for radio astronomy. The following section describes six techniques which would need to be incorporated to provide a robust and versatile distributed timing system that meets all the SKA's requirements.

4.1 Optical Fibre Stabilisation

Mechanical, acoustic, and thermal perturbations on the optical fibre cause variations of the fibre's optical path-length, thereby resulting in fluctuations of the phase, frequency, and arrival time of the transmitted signal. To counteract these external perturbations, a fibre link stabilisation system is required to ensure that the synchronisation signal is distributed to the remote sites with a frequency stability that surpasses the specified SKA requirements.

Figure 5 shows a schematic diagram of a typical fibre link stabilisation system. At the local site, a transmitting laser is locked to a stable frequency reference; this could be a single atomic clock such as a hydrogen maser, or an ensemble of clocks that can provide ultra-high stability over a much larger range of time-scales. The majority of the laser output power is passed through the actuator, a device that is used to modify either the physical length of a small section of fibre (a fibre stretcher) or alter the phase of the transmitted laser light (an acousto-optic modulator). The laser light is then injected onto the fibre link. At the remote site, part of the light is returned along the same path back to the local site, where it is mixed with a portion of the original transmitted light, and the resulting beat signal is detected using a photodetector. The variations of this beat signal are a direct measure of the mechanical, thermal, and acoustic fluctuations of the fibre link.

The beat signal is filtered, integrated, and inverted before being applied to the actuator. With this input, the actuator attempts to alter the link length (if the actuator is a fibre stretcher) or vary the optical phase (in the case of an acousto-optic modulator) in such a way that any difference between the returned signal and the reference signals is driven to zero. Furthermore, as the returned signal has passed through the actuator and the fibre loop twice, and because the actuation mechanism has the same effect on light traveling in either direction, the link fluctuations are also cancelled at the remote end of the link.

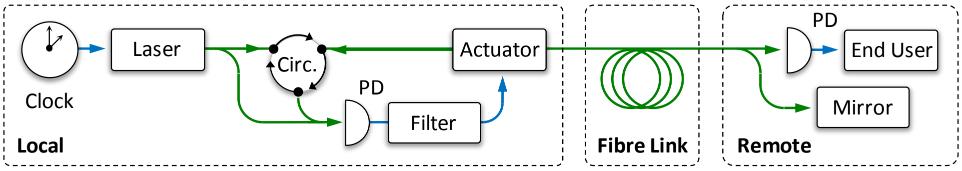

Figure 5: Schematic diagram showing the basic elements of a typical optical fibre link stabilisation system. Electronic signals are shown in blue and optical signals in green. Circ., optical circulator; PD, photodetector.

4.2 Transfer on Fibre Links Shared with Data Links

A single optical fibre can accommodate dozens of independent laser signals simultaneously, each with a slightly different wavelength; this scheme is known as wavelength domain multiplexing. This allows time and frequency signals to be transmitted on any of the extensive optical fibre networks that are already used by the telecommunications industry. In these telecommunications networks, links longer than around 100 km require the use of optical amplifiers to counteract the attenuation of optical fibre (typically 0.2 dB per kilometre). In order to minimise the number of amplifiers required on a particular link, and thereby reduce the cost of the associated infrastructure such as remotely powered huts, the telecommunications industry uses amplifiers with the highest gain possible. By placing directional isolators (components that allow light to pass in only one direction) within the optical amplifiers, the gain can be increased by an additional factor of two before the amplifiers saturate. Therefore, telecommunications protocols dictate that two separate optical fibres are to be used; one for transmitting and the other for receiving.

However, as described in the previous section, for effective link stabilisation it is critical that the transmitted signal is perturbed by the same fluctuations on the outgoing and return trips along the optical fibre link. This implies that the timing signals must be transmitted and returned on a single fibre. Therefore, many experimental links around the world rely on access to dark fibre (fibre that is not used for telecommunications data transfer) to avoid this limitation. However, a technique has been developed [18, 19] (see Figure 6) which allows timing signals and telecommunications data to co-exist on the same fibre network. Commercial technology exists (add-drop multiplexers) which can physically separate the specific timing signal wavelength from the remainder of the data wavelengths. The data wavelengths pass though the standard optical amplifier, while the timing signal wavelength is directed through a custom bi-directional optical amplifier (simply an amplifier with no isolators), before being combined again with the rest of the data wavelengths.

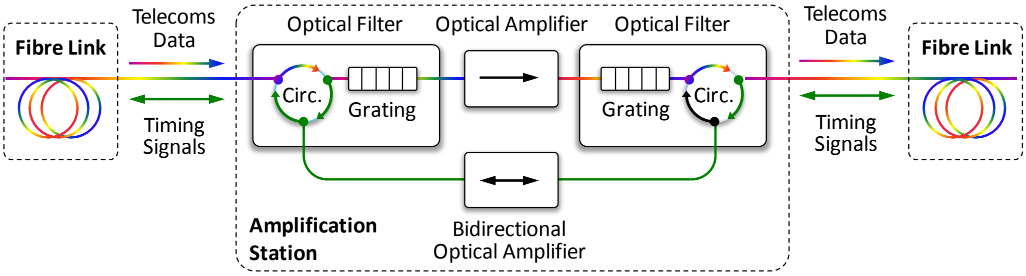

Figure 6. Schematic diagram of an amplification station that separates the counter-propagating timing signals from the remainder of the uni-directional data signals. This allows bi-directional amplification of the timing signals before they are recombined with the data signals. Optical timing signals are indicated by the green lines and multiple data signals by the rainbow lines. Circ., optical circulator.

4.3 Continental Scale Transfers

As shown in the previous section, optical amplifiers are required every 80-100 km to counteract the attenuation of optical fibre. However, for the following two reasons the length of a timing link cannot be continuously increased, and a fundamental limit is reached at a maximum length of around 500-1,000 km (the exact value depends on the physical characteristic of the link). The first reason is that optical amplifiers amplify noise as well as signals; so after multiple amplification stages, the signal-to-noise ratio becomes too small for practical use. Secondly, due to the finite speed of light, the round-trip time becomes ever longer as the link length is increased. As the sensing signal must sample the same fibre fluctuations on the transmitted and returned paths, only low frequency noise is sensed and can therefore be supressed. Noise with frequencies above the inverse of the round-trip time is de-correlated by the time the sensing signals returns. In other words, the bandwidth of the feedback loop (and thus also the magnitude of noise suppression at lower frequencies) is reduced as the fibre link length is increased until it is no longer possible to supress the majority of the fibre noise.

To get around this issue, we can employ complete optical regeneration every 500-1,000 km along the length of the link [10, 18]. As shown in Figure 7, this can be achieved by mixing the incoming transmitted signal with a reference laser located at the regeneration station. The resulting beat signal is detected on a photodetector, electronically filtered and amplified, and then used to make small corrections to the output of the regeneration laser. This process effectively transfers the stability of the incoming laser signal onto the regeneration laser. The regeneration laser output is then transmitted along the next section of the fibre link.

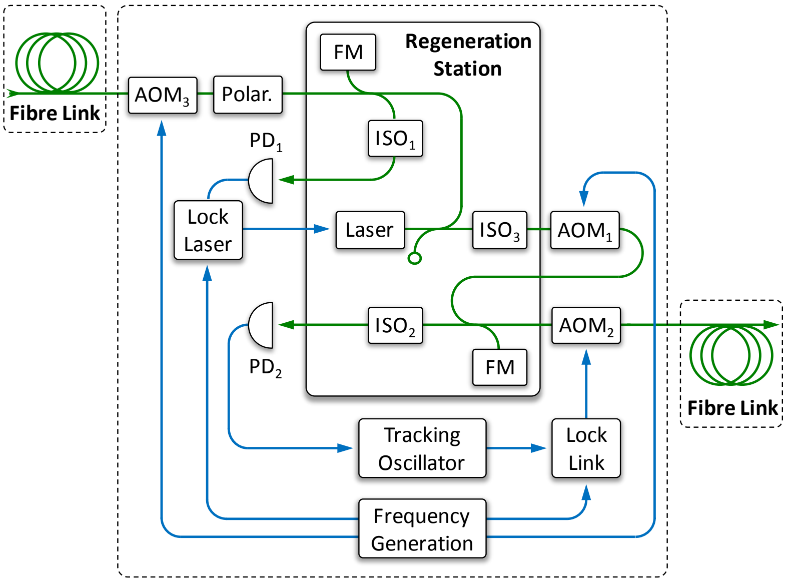

Figure 7. Schematic diagram of a possible repeater station implementation. Electronic signals are shown in blue and optical signals in green. AOM, acousto-optic modulator; Polar., polarisation controller; FM, Faraday mirror; ISO, optical isolator; PD, photodetector. Adapted from [18].

4.4 Microwave Frequency Transfer

Despite the superior performance achieved with optical frequency stabilisation techniques, radio- or microwave-frequency amplitude modulation techniques have the benefit of easily providing a signal at the remote site for direct application in electronic systems. In contrast, an optical frequency signal can only be used in electronic systems after down-conversion with a high-cost optical frequency comb synthesiser [10, 11] located at the remote site. On the other hand, the dissemination of an optical frequency comb spectrum can deliver both optical and microwave signals to the remote site thereby incorporating the advantages of the two methods above. However, as the transmitted comb spectrum spans a wide wavelength range, this technique cannot be used on fibre links that concurrently transmit telecommunications signals.

We have recently developed a novel technique [20] which simultaneously stabilises transmitted optical- and microwave-frequency signals (see Figure 8). We use a special telecommunications-grade modulator to produce an optical carrier signal with a single optical sideband. This results in two coherent optical frequency signals of equal magnitude, separated by a microwave frequency difference. The link fluctuation sensing and feedback technique is insensitive to the additional optical sideband and therefore the stabilisation scheme is otherwise identical to the standard all-optical approach outlined in Section 4.1 above. We have shown theoretically and experimentally that by suppressing fluctuations measured by the transmitted optical carrier, fluctuations in the microwave frequency difference are also suppressed. Furthermore, the microwaves fluctuations are suppressed by almost the same factor as the optical fluctuations, resulting in the ability to transfer microwave frequencies with unparalleled precision.

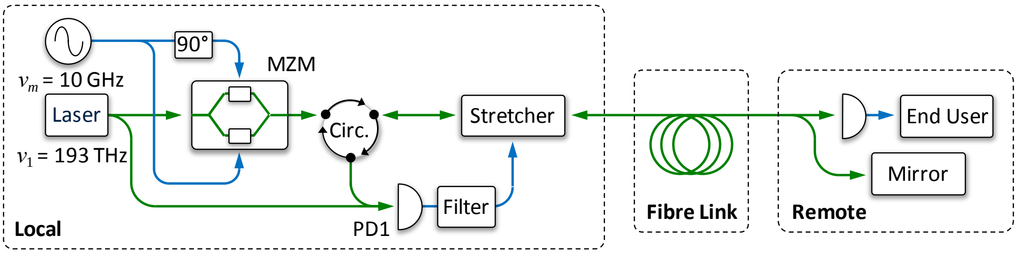

Figure 8. Schematic diagram of a dual optical/microwave frequency transfer technique. Electronic signals are shown in blue and optical signals in green. 90°, phase shifter; MZM, dual drive Mach-Zehnder modulator; Circ., optical circulator; PD, photodetector. Adapted from [20].

4.5 Absolute Time Transfer

The ability to precisely transfer ultra-stable microwave signals to the SKA antennas sites will make it possible to synchronise the array, and thereby replace the need for hydrogen masers located at each site. However, the data still needs to be referenced with respect to absolute time so that the appropriate delays can be applied before the data are processed by the central correlator. In existing telescope arrays this is achieved using timing signals obtained from GPS receivers that are co-located with each antenna.

However, it is also possible to use stabilised optical fibre links to transmit accurate absolute time. Recently, absolute time with an accuracy of 250 ps and long term stability of 20 ps has been transferred across a 500 km optically-stabilised fibre link [21]. The timing information was encoded as a spread spectrum signal via phase modulation onto an optical carrier using commercially available two-way satellite timing modems as shown in Figure 9.

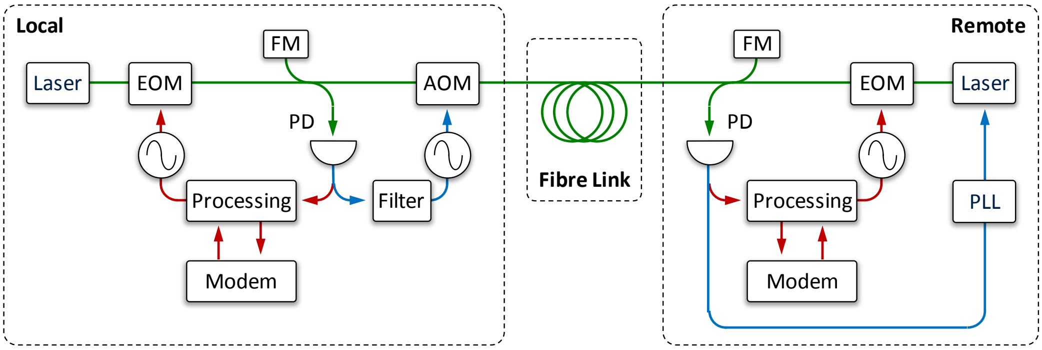

Figure 9. Schematic diagram of an absolute time transfer system. Electronic link stabilisation signals are shown in blue, electronic timing signal are in red, and optical signals in green. EOM, electro-optic modulator; FM, Faraday mirror; PD, photodetector; AOM, acousto-optic modulator; PLL, phase lock loop. Adapted from [21].

In this technique, the acousto-optic modulator is used to stabilise the optical link just as in the standard technique described in Section 4.1. The laser at the remote end of the link is used to regenerate the incoming signal using a phase lock-loop (see Section 4.3 for more details) thereby making it possible to optically stabilise the 500 km link. The timing signals are encoded by the modems onto the optical frequency using an electro-optic modulator.

4.6 Point-to-Multipoint Transfer

The optical stabilisation technique described in Section 4.1 is able to cancel link fluctuations at the remote end of the link. But what happens when there is more than one remote end? Because standard stabilisation techniques uses an actuator located at the local end to modify either the link length or the phase of the transmitted light, there can only ever be one remote location for which the link fluctuations are optimally supressed. A new technique is required for systems like the SKA which have one central node and many branching end sites. Furthermore, the ability to add new branches into established links will be crucial because the SKA will be built-out progressively and new antenna stations need to be added seamlessly without disturbing the existing synchronisation system.

We recently demonstrated a novel technique that places the actuator at the remote site [22]. As shown in Figure 9, an optical frequency is transmitted along the fibre link from the local site to a remote site. A portion of the power is sent to a photodetector while the remainder is transmitted back to the local site. Once there, it reflects off a mirror and passes along the link for a third time before also ending up at the photodetector. This results in an electronic signal that is proportional to the difference in fluctuations between the single-pass and the triple-pass signals. After being filtered, this signal is applied to the actuator which acts to drive this difference to zero. In doing so, it also applies the appropriate correction to the original transmitted signal such that fibre fluctuations are supressed at the remote site.

As this technique does not interfere with the transmitted optical signal, the fibre can be branched multiple times with the signal sent to different remote sites, each employing a near identical stabilisation system. As each remote site imparts a unique frequency shift to the incoming signal via an AOM, the other remote sites' reflected signals can be filtered out using a simple electronic band-pass filter.

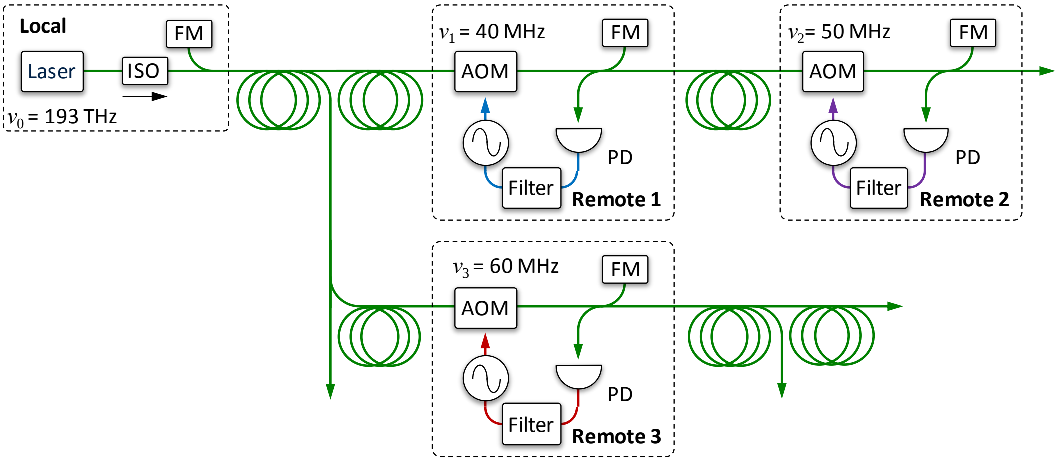

Figure 9. Schematic diagram of a point-to-multipoint implementation demonstrating several different connection architectures. Electronic signals are shown in blue, purple, and red, while optical signals are shown in green. ISO, optical isolator; FM, Faraday mirror; AOM, acousto-optic modulator; PD, photodetector. Adapted from [22]

5. Discussion and Conclusions

Section 4 outlined six time and frequency techniques that when combined would comprise a robust and versatile distributed timing system that meets all requirements of the SKA. However, while some of these individual techniques already incorporate multiple elements (for example, optical and microwave frequencies have been simultaneously transferred on active telecommunications networks), the challenge still remains to demonstrate a single combined system that incorporates all the elements listed in the previous section. Combining the following four elements should not prove to be difficult: optical fibre stabilisation (§4.1), transfer on fibre links shared with data links (§4.2), continental scale transfer (§4.3), and microwave frequency transfer (§4.4).

However, with current techniques, it may be difficult to reconcile absolute time transfer (§4.5) and point-to-multipoint transfer (§4.6). This is because accurate time transfer techniques require a two-way exchange of information, while point-to-multipoint transfer depends on a static source at the local site. If a solution to this issue cannot be found, then perhaps only one of these elements can be integrated into the combined system. For the case of the SKA, it makes clear sense to incorporate the point-to-multipoint technique. A separate solution for time transfer with sufficient accuracy for radio astronomy already exists in the form of GPS. Having an additional GPS receiver at each telescope site is not only a cheap source of absolute time, but it also provides a useful position reference. Combining and then testing all these elements on an appropriately large scale will require access to a continental-sized optical fibre network. National time and frequency distribution networks on the order of a few hundred kilometres are being established in France and Germany. However, larger-scale network deployment in US and Europe is hindered by complex and expensive access to optical fibre infrastructure.

In Australia, the NTFN collaboration is fortunate to work in partnership with AARNet which owns several thousand kilometres of optical fibre throughout Australia. We have recently demonstrated radio-frequency transfer with bi-directional optical amplification over a 300 km link around Canberra, and in the next few months, we also expect to conduct a radio astronomy experiment over the 160 km fibre link between the Australia Telescope and the telescope at Mopra. Thanks to our partner CSIRO, we also have access to the 820 km fibre link between Perth and the Murchison Radio Observatory (MRO), which is the location of ASKAP, MWA and the site for the Australian component of the SKA. Furthermore, the NTFN collaboration was recently shortlisted from 175 applicants to be considered for $4M in funding to deploy a 3,000 km time and frequency network from Adelaide to Brisbane, passing through Melbourne, Canberra, and Sydney, as well as the radioastronomy telescopes in central NSW that comprise the Australian Long Baseline Array. On the time-scales of SKA Phase 2, we plan for an eventual extension to include Perth and the MRO, a total network of 6,000 km, over six times the length of anything possible in the rest of the world.

Acknowledgements

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