The Square Kilometre Array: the Notion of Timing and Synchronization

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Abstract— From dark matter to redshift and expansion, the universe continues to intrigue and baffle scientists at large. The Square Kilometre Array (SKA) is an international science endeavor aiming to construct the world's most sensitive and largest radio telescope, on the African continent. By 2016, the MeerKat antenna array will consist of 64 interconnected receptors. Highly stable time and frequency clock signals will be distributed from the Karoo Array Processing Building (KAPB) to the individual dishes across a total of 170 km of optical fibre to the digitizers mounted on the receiver indexers. This article gives a brief description of the technical requirements stipulated for the SKA and the role of timing and synchronization within the MeerKat antenna array. Furthermore, this paper proposes a timing and frequency dissemination system across an optical fibre network for applications such as the SKA.

Keywords—Optical fibre, Square Kilometre Array, synchronization, timing, VCSEL .

I. Introduction

The Square Kilometre Array (SKA) is an international science endeavour aspiring to construct the most powerful radio telescope in the field of radio astronomy. Collectively, the large number of smaller dishes making up the SKA antenna array has a combined effective collecting area of one million square metres, making this attribute a crucial feature of the SKA [1]. Upon completion, the SKA will be the most powerful and sensitive radio telescope facilitating the exploration of the cosmic dawn and the study of how galaxies were formed [2], [3]. Moreover, the SKA will provide high-resolution three-dimensional images of cosmic magnets, investigate the ever expansion of the universe and have the ability to detect weak extraterrestrial radio wave [4], [5], [6].

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The SKA will be co-hosted in Australia and Africa, however South Africa is not the only African partner hosting SKA. There are eight additional African associate countries contributing to the radio telescope network array, within the SKA. The South Africanforerunner to the SKA, the MeerKAT telescope array, will encompass 64 interlinked receptors whereas the 36 dishes making up Australian Square Kilometre Array Parthfinder (ASKAP) forms the Australian precursor of the SKA. Located in a desert region within South Africa, the first seven dishes, KAT7 seen in figure 1, have been installed and is currently being further developed into MeerKAT. The MeerKAT radio telescope will be integrated into the mid-frequency range element of SKA phase 1 [5], [7].

The SKA telescope array will be implemented in two stages, construction of SKA phase 1 will commence in 2016 and the assembly of SKA phase 2 will begin in 2018. SKA phase 1 will implement approximately 10% to the total antenna array, data collecting area of SKA phase 2 [9]. The first phase of the project will be divided between the continents of Africa and Australia, consisting of SKA 1 Mid, SKA 1 Low and SKA 1 Survey [5]. In SKA phase 2, it is estimated that 3000 SKA mid frequency antennas will be developed and installed on the African continent.

Fig. 1KAT-7 telescope array [8].

With the largest concentration of antennas located in South Africa and each African associate country (Botswana, Kenya, Ghana, Madagascar, Mauritius, Mozambique, Namibia and Zambia) accommodating 40 dishes [9].

In this paper we present a preliminary, simulated clock distribution system whereby we disseminate a 1552.52 nm optical signal along 1 km G.652 optic fibre cable. The simulated system is partly based on RF frequency mixing similar to [10]. Furthermore, we propose the use of a Vertical Cavity Surface Emitting Laser (VCSEL) to acts as the actuating component and ultimately compensating any phase fluctuations along the optical fibre.

The SKA telescope array is required to make synchronous outer space observations, requiring precise and accurate timing, with the dishes situated at diverse locations. The concept of synchronization and timing is discussed in the section that follows.

II. CONCEPT OF TIMING AND SYNCHRONIZATION FOR THE SKA

To accommodate the rigorous sensitivity and resolution stipulations needed for present day radio wave astronomy, a dispersed antenna array system is required with long baselines, generating enormous amounts of data [1]. Optical fibre will be an essential component for the SKA since it is required to transport huge amounts of scientific data from individual receptors to a central processing unit. It is estimated that approximately 160 Gbps of data will be disseminated along optical fibre, from each antenna to a central super computing processor. The ability of an optical fibre to aggregate huge volumes of data over lengthy distance at extreme speeds can increase the sensitivity of the SKA radio telescope. Timing and synchronization within the SKA network system is essential, as it is needed to meet multiple requirements. At both the MeerKATASKAP sites, a central reference clock system will be required. Precise time and frequency reference signals are disseminated via optical fibre, from central clock, to the digitizer located on each antenna within the telescope network array [7]. This exercise ensures that there exists phase cohesion amongst the individual receptors within the SKA telescope. Furthermore, the reference clock delivers absolute time for antenna pointing, system management and beam steering. Since pulsar monitoring will be one of the studies conducted with the SKA telescope, it requires timing accuracies of 1 ns to 10 ns over a 10 year period. Therefore, the central clock system will further provide extremely accurate long-term timing for transients and pulsars [5], [6].

Synchronization and timing across optical fibre within the MeerKAT telescope will be achieved by producing the precise frequencies at the Karoo Array Processing Building (KAPB). A total of 170 km of fibre will be utilized, buried approximately 1 m below the earth's surface [5], [7]. Phase stability is likely to be affected by the ambient temperature fluctuations, changing environmental conditions, varying polarization mode dispersion (PMD) and fibre birefringence [5]. However, with the introduction of advance concepts such as coherent detection, higher order modulation formats and the dawn of low PMD and dispersion shifted fibres, birefringence and PMD may no longer be realized as convoluted.

III. PROOF OF CONCEPT

Figure 2 illustrates the schematic diagram of the frequency transfer system across 1 km G.652 single mode fibre. The crucial components at the transmitting site T_x are the signal generator and a VCSEL laser source.

At the T_x end, a 1552.52 nm optical carrier is modulated using a 1 GHz clock signal. The expression describing the voltage generated by signal generator 1, shown in figure 2, is given as

$$V_{Tx} = \cos[\omega_1 t + \theta_1] \quad (1).$$

For the convenience of the simulation, signal generator 1 was additionally utilized as the reference frequency source. The oscillating reference signal can be described as

$$V_{ref} = cos[\omega_{ref} t + \theta_{ref}] \quad (2)$$

Once emitted from the VCSEL, the modulated optical signal is transmitted along the fibre from the T_x site toward the receiver end, R_x. At the R_x end, a certain percentage of the optical signal is converted back to an electrical signal expressed as

$$V_{Rx} = cos[\omega_1 t + \theta_1 + \theta_{fibre}] \quad (3),$$

whereθ_{fibre} is the phase variation induced by the optical fibre, due to temperature change and PMD. The unconverted optical signal is then transmitted back to the $T_x$unit. After completing the round-trip, the returned optical signal is converted to an electrical form described by

$$V_{Rx-Tx} = cos[\omega_1 t + \theta_1 + 2\theta_{fibre}] \quad (4)$$

At this juncture, the error signal is being created by virtue of a two-stage frequency mixing process.

Mixing product one, expressed as

$$V_{M1} = cos[2\omega_1 t + 2\theta_1 + 2\theta_{fibre}] \quad (5)$$

was generated by up converting V_{Tx} and V_{Rx-Tx}. With the assistance of signal generator 2,as illustrated in figure2, the error signal was finally generated as follows. Down mixing

$$V_2 = cos[\omega_2 t + \theta_2] \quad (6),$$

from signal generator 2 and V_{M1}, the following error signal was produced,

$$V_{error} = cos[\{2\omega_1 - \omega_2\}t + \{\theta 2_1 + 2\theta_{fibre} - \theta_2\}] \quad (7).$$

The oscillation frequency of signal generator 2 was 2 GHz. The error signal described above will be used to drive the laser diode controller (LDC), which in turn will cause the optical output signal from the VCSEL to either shift forward or backward, as result of the inherent chromatic dispersion of the fibre. Furthermore, the error signal will be maximized when the phase difference between V_{Tx} and V_{Rx} is zero. The two-stage mixing process ensures that the signal at the Rx site, after one trip, will always be

$$V_{Rx} = cos[\omega_{ref} t + \theta_{ref}] \quad (8),$$

if and only if $\omega_2 = 2\omega_{ref}$ and $\theta_2 = 2\theta_{ref}$.

IV. COMPENSATION RESULTS

Figures 4 (a) and (c) shows the relative phase differences between the reference $V_{ref}$and the received V_{Rx}signals, at the induced fibre delays, before the phase offset was applied. Whilst, figures 4 (b) and (d) illustrates the relative phase differences between the reference V_{ref} and the received V_{Rx} signals after the phase offset was applied. The offset angle was determined by sweeping the error signal V_{error}, generated after a series of mixing operations. Figure 3 is an illustration of the measured error signal during the sweep process for a 50 ps induced fibre delay. It is evident from figure 3 that the maximization of the error signal V_{error} occurs when thephase offset angle between

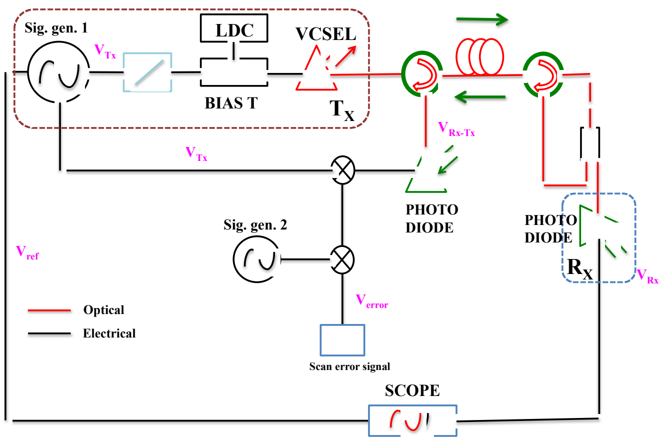

Fig. 2 Block diagram illustrating the simulated electro-optic frequency dissemination system

V_{Tx} and V_{Rx} is 20 degrees, for a 50 ps introduced fibre delay. Furthermore, from the information obtained in figure 3 and the results displayed in figure 4 (b), it is clear that the maximization of the error signal emerges when the phase between V_{Tx} and V_{Rx} is zero. This observation further infers that once the phase correction is applied, the phase difference between the reference V_{ref} and the received V_{Rx} signals is zero, as illustrated in figure 4 (b).

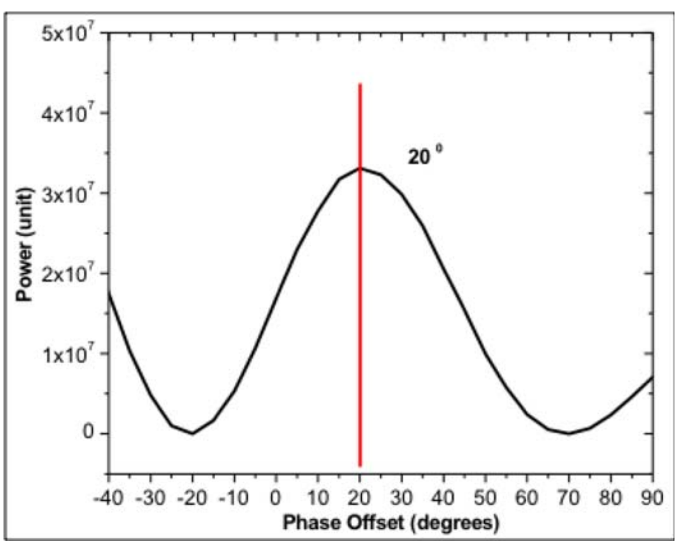

Fig. 3Error signal created after the two step mixing process for a 50 psfibre delay

It is evident from figures 4 (a) and (c) that for any delay introduced to the fibre the phase of the uncorrected signal (red signal) drifts accordingly, portraying the relationship between ambient temperature or environmental conditions and phase of the transmitted signal along the fibre. However in a feedback phase correction system, the error signal generated will ensure that the phase of the transmitted signal is always identical to the phase of the reference signal. As illustrated in figures 4 (b) and (d).

V. CONCLUSION

The optical fibre network forming backbone of the SKA telescope array is an extremely crucial component within this astronomical science project. We were able to demonstrate frequency dissemination system across an optical fibre link. It is evident from figures 4 (b) and (d) that the system described in figure 2 is able to correct for any phase shift induce in the fibre as a results of temperature influences or environmental conditions. Moreover, the most important step that follows will be to experimentally verify that the system described in this paper works.

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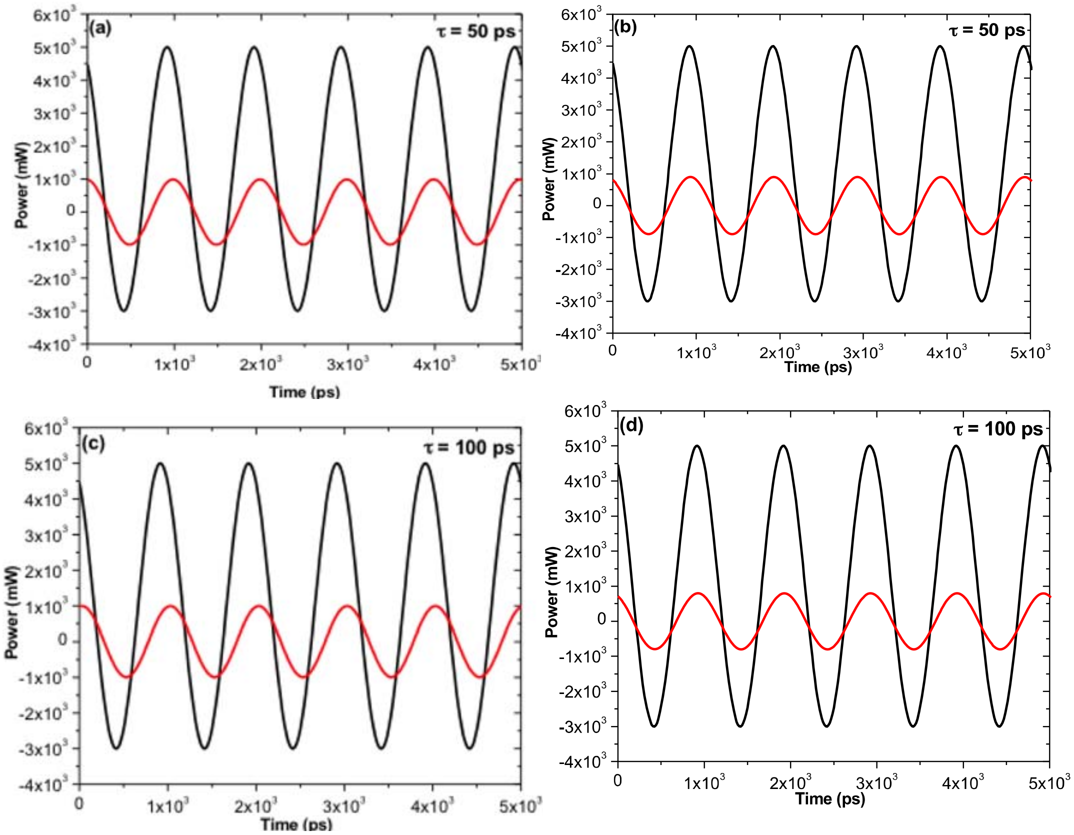

Fig. 4Illustration of the relative phase shift between the reference signal $V_{ref}$and the received signal V_{Rx}before and after the phase offset is applied. 50 ps and 100 ps induced fibre delays were employed as shown in (a), (b) and (c), (d) respectively.