Incoherent clocking in radio interferometers and application to the ngVLA

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Incoherent Clocking Concept

Fundamentally in a coherent array it is necessary to continuously align the wavefront from the source prior to correlation and beamforming. In the conventional approach, this is done using coherent LOs and digitizer clocks to do the high temporal-precision portion of this alignment, followed by digital delay and phase tracking according to a model of the wavefront delay for a known LO, and then periodic calibrator source observations to facilitate final alignment such that the "white light fringe", on every correlated baseline, stays near zero relative delay. However, the first part of this process can be done differently by using free-running and incoherent clocks at each antenna, measuring the phase/frequency of each one in a common clock domain, and then digitally correcting the data—amounting to delay and phase corrections—prior to wavefront delay+phase correction and correlation and beamforming. A hint of this process is already evident in VLBI: each antenna uses its own independent highly stable LO and the VLBI correlator is subsequently provided with, and applies, GPS-determined 'clock corrections' to extend coherence. In the SKA1 Mid telescope array, where all receivers use direct digital sampling, each antenna is fed with a *different* and a priori-known digitizer clock frequency, locked and round-trip phase-corrected to the same central Hydrogen maser clock. This ensures that, after digital correction and re-sampling to a common clock frequency, no digitizer-clock-dependent spectral artefacts correlate, improving the RFI robustness of the telescope to self-interference [1] (and, it has been found, to improve 'spectral confinement' of RFI through the decorrelation of reject-band aliased spectral components from digital filtering). The incoherent clocking method described here [2] is simply an extension of the SKA1 Mid method except that the LO/digitizer clocks at each antenna are independent and free-running, accurately measured, and with such measurements used to correct the data prior to correlation and beamforming. Since antenna clocks across the array are not coherent, the same or even better RFI-robustness as in the SKA1 Mid telescope is obtained.

Incoherent Clocking Operation

A block diagram of the general operation of the incoherent clocking method is shown in Figure 1. Optional down conversion and digitization of data at each antenna occurs using its own independent LO frequency *aLOn(t)*. Digitized science data is sent to the correlator site along with a digital 'tracer' of *aLOn(t)* on a digital 'tracer link' (TL). The TL need only retain the real-time phase/frequency information of *aLOn_tr(t)* (the tracer frequency) inasmuch as needed to accurately extrapolate to the changing phase/frequency of *aLOn_netLO(t)* and *aLOn_adc(t)* that needs correcting in the data. The frequency of the digital tracer is measured and tracked to very high accuracy using a digital tone extractor, as indicated in Figure 2.

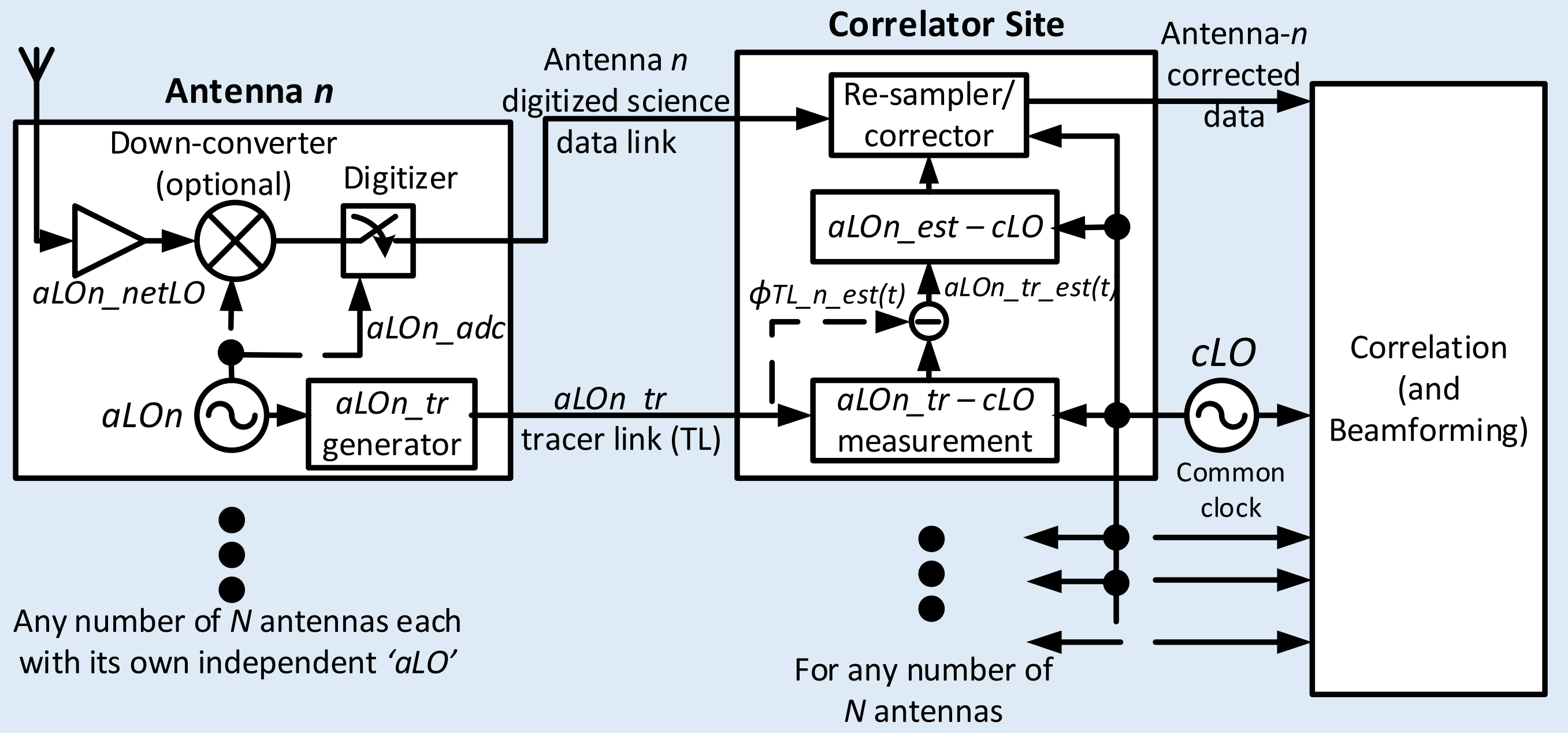


Figure 1: Block diagram of the general operation of the incoherent clocking method.

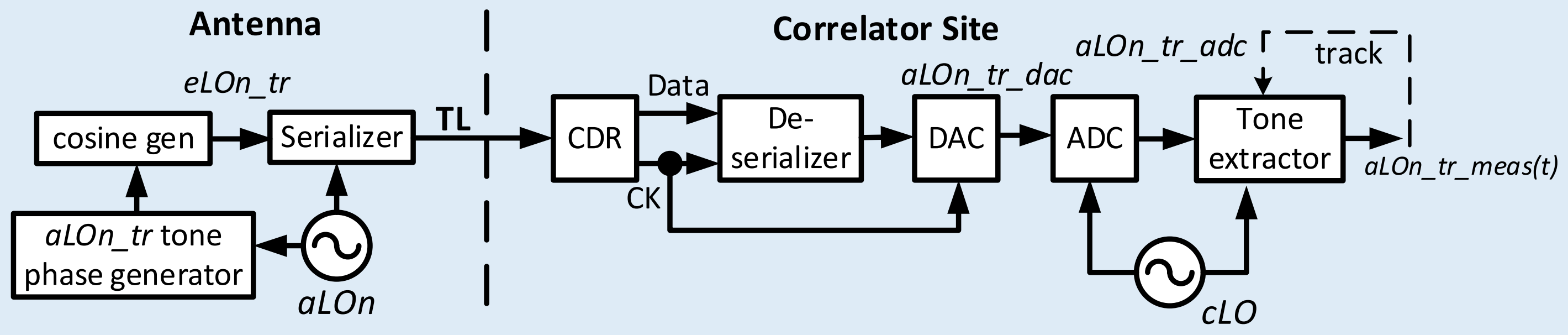


Figure 2: Block diagram to measure and track the *aLOn_tr* tracer digital tone using a digital complex tone extractor.

Of course, changes in the tracer link delay, *τ_TL(t)*, for any appreciable TL length has an effect on the measured tracer phase/frequency vs time as indicated in Figure 1. To measure this, of course, a round-trip measurement is necessary: as shown in Figure 3, simply turn around the digital signal and measure its phase/frequency changes relative to the original digital tracer. Use these measurements to adjust the *aLOn_tr(t)* measurement to obtain a *ϕTL_n_est(t)*-corrected estimate, *aLOn_tr_est(t)*, of the antenna LO and use it for correcting the data. Once *aLOn_est(t)* is available, it is used to re-sample and, if necessary, phase-correct the data in the "Re-sampler/corrector" circuit, shown in more detail in Figure 4. This circuit primarily consists of a real-time sample-by-sample interpolating O(80)-tap FIR filter, followed by a mixer to perform any phase corrections needed (for Nyquist zone-1 direct digitization, no phase corrections are required), driven by an *aLOn_est- cLO* phase synthesizer. What comes out is digital data corrected into the common *cLO* clock domain, ready for correlation (and beamforming).

Abstract

Distribution of a common high temporal-fidelity coherent clock to all antenna receivers/digitizers in a radio telescope array is essential for its operation. This can present challenges over extended arrays operating at high frequencies using round-trip real-time distribution methods, or for low-cost many-element arrays. Here, a different approach is described wherein: 1) each antenna operates using its own independent LO, 2) the phase/frequency vs time of each LO is measured at a central site, using a real-time digital 'tracer' frequency transmitted over a digital link using COTS digital methods, and 3) the digitized science data is digitally corrected according to the measurement prior to correlation and beamforming. The general method is described and then a notion of how it might be applied to the ngVLA is briefly discussed.

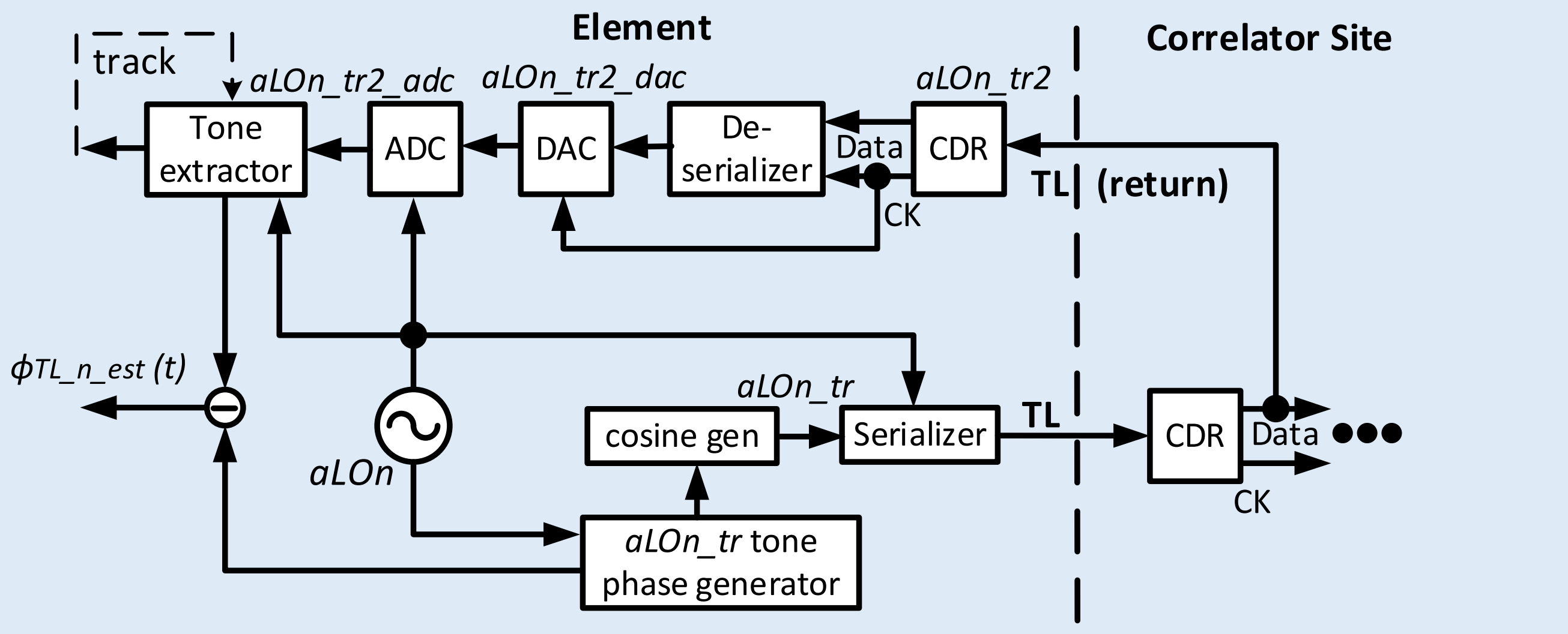


Figure 3: Digital round-trip measurement of the tracer, to remove tracer link delay variations, *τ_TL(t)*, entangled in tracer phase/frequency measurements as an additional *φTL_n(t)* term.

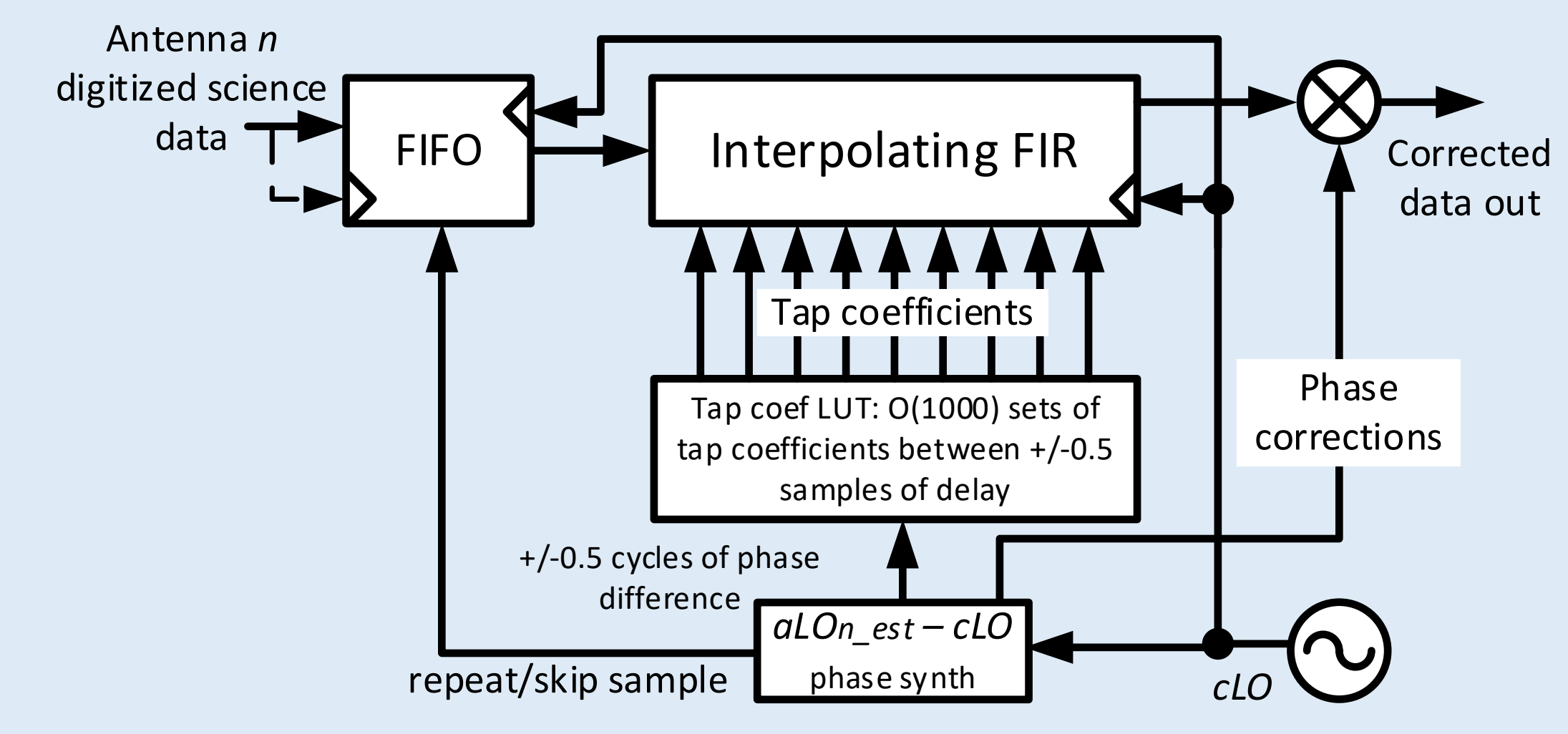


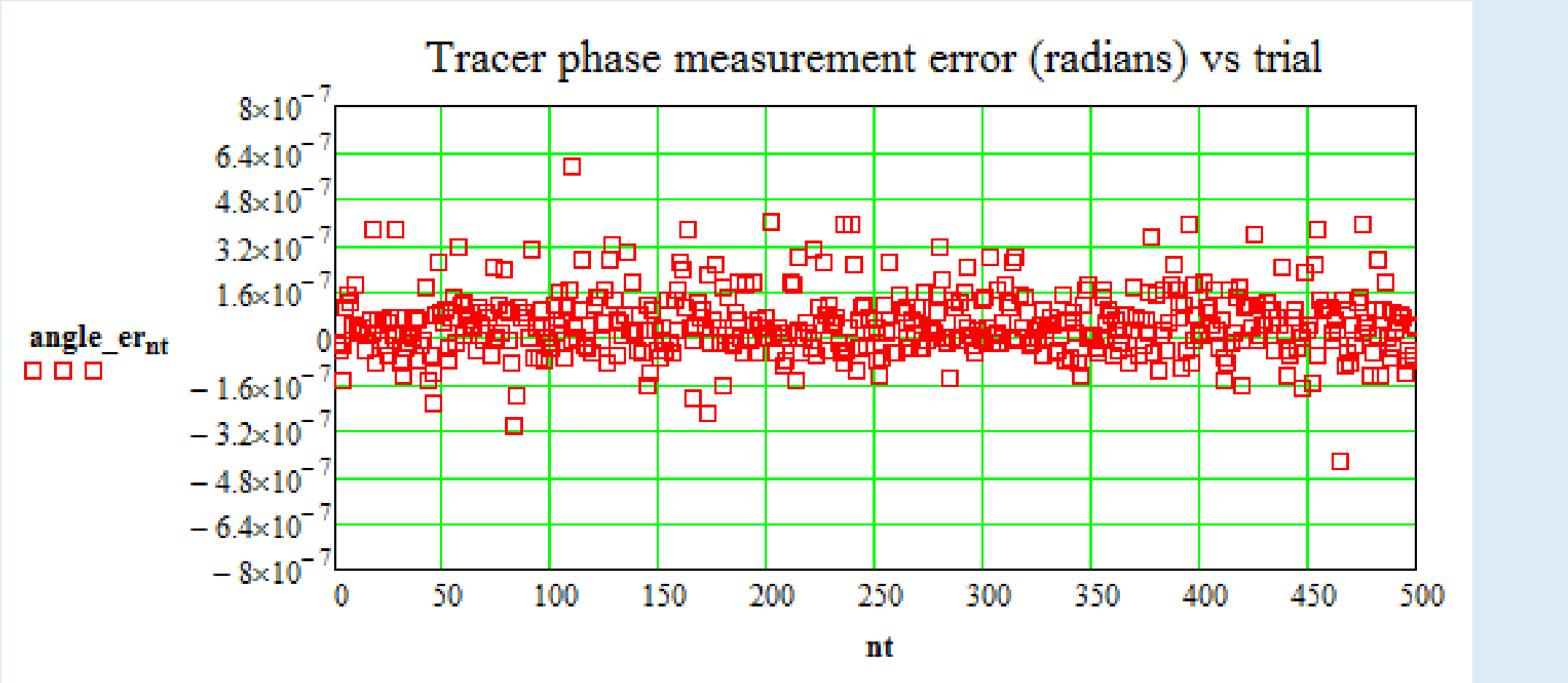
Figure 4: The digital delay and phase correcting circuit.

Tracer and Tracer Link (TL) Issues Discussion

Described thus far are the key components of the incoherent clocking method. There are a number of subtle issues regarding the tracer link that warrant pointing out. (1) The DAC/ADC pairs needed to cross the *aLOn(t)/cLO* clock domain, i.e. to transfer *aLOn_tr(t)* phase/frequency information into the *cLO* clock domain where it is measured should, under some circumstances, be able to be deleted with requisite operations performed digitally (TBC). (2) It was stated that the TL can use a digital link which, for the ngVLA, would be a fiber-optic link. However, the restriction is that this link must retain the real-time *aLOn_tr(t)* phase/frequency information intrinsic to *aLOn(t)*. In practice this means that only CDR (Clock-Data-Recovery) re-timing is used in TL repeaters and that all serial transceivers (e.g. SERDES in chips/FPGAs that are part of this link) are operated in raw mode with no rate-matching (e.g. via code word insertion/deletion and independent oscillators). This means that the TL needs to be a dedicated link, albeit with COTs components. (3) To effectively determine *ϕTL_n_est(t)* using a round-trip measurement, all outbound and inbound components should be as matched as possible. For example, fiber lengths/runs should be matched and undergo the same CTE effects. (4) Since science data is digitized, it can be buffered at the correlator site to match the time it takes to make the *aLOn_tr_est(t)* measurement (i.e. the measurement interval MI), and then *applied to the same data on which the measurement was made*. Furthermore, since the phase/frequency of *aLOn(t)* is changing with time, the '*aLOn_est–cLO*' synthesizer can include this change such that it accomplishes piecewise linear tracking of *aLOn(t)* rather than stair-step tracking, further improving the accuracy of the correction and increasing the d(*aLOn(t))/dt* that can be tracked and corrected for. (5) Due to (2), if the TL and the science data are integrated into the same fiber link (and same color) then those restrictions also apply. By keeping the TL separate from the science data, the science data link can use standard COTS equipment and methods for transmission with no need to retain real-time *aLOn(t)* information. In this case, the round-trip measurement measures delay, a 1PPS marker at the correlator site is negatively delayed by that amount and transmitted to the antenna via the return trip, and then it is embedded into the science data stream etc. (6) The accuracy of the tracer phase/frequency measurements depend on its SNR—since the tracer is a single tone, it can be digitally bandpass-filtered prior to tone extraction to increase its SNR and decrease the error in *aLOn_est(t)*. (7) Further tracer implementation short-cuts/optimizations can be taken to minimize TL bandwidth used. (8) Generally, for any application there is a *dϕTL(t)/dt*, *aLO* stability, TL length, and MI parameter space to optimize.

Example Implementation

A 100 Mbps full-duplex digital fiber link using COTS fiber modules implement the TL, and one or more separate 100GBASE-XR links are used for digitized science data. At this speed, a ~2 MHz 8-bit tracer tone (*aLOn_tr*) is sampled at ~10 Ms/s, digitally derived and digitally synthesized from each antenna's *aLOn*. The antenna digitizer clock *aLOn_adc* runs at ~10 Gs/s and its *aLOn_netLO* = ~100 GHz. The tracer is transmitted to the correlator site on SM fiber using a 100 Mbps fiber transceiver module such as the EOLS-1503-X SFP, which has a 200 km reach. At the correlator site, the 2 MHz 8-bit digital tone is digitally up-sampled to ~500 Ms/s, rounded to 7 bits and grey-code encoded, and sampled into the *cLO* clock domain (introducing some sampling jitter, the effects of which are TBC), where it is bandpass-filtered to produce an 18-bit (full-scale) tone. Using a 0.1 msec measurement interval (MI), the 18-bit complex digital tone extractor yields an RMS measurement accuracy of ~1.4e-7 radians. From this, the extrapolated phase of the digitizer clock—needed by the digital re-sampler—has an error of ~1e-4 clock cycles and the extrapolated phase of the 100 GHz LO—needed for the corrector phase rotator—has an error of ~0.4 degrees. (This example ignores the round-trip TL measurement, however, it should be able to be measured with similar accuracy as the same methods are employed on the return.)



Potential ngVLA Implementation

In the ngVLA implementation, it is beneficial to integrate the tracer with the science data on the 56 Gbps digital links. In this case, no digital tracer tone is developed at the antenna, rather at the correlator site the recovered clock is used to drive a digital tone synthesizer in the antenna clock domain, then transferred into the common clock domain and digitally tone-extracted as above. Similarly for the round-trip TL measurement: only the change of *ϕTL_n_est(t)* relative to a "coherence start time" needs to be measured and so the absolute initial phase of the tracer at the correlator relative to that at the antenna can be arbitrary. To determine and compensate for tracer link delay, one of three methods could be used: (1) The round-trip delay is measured using the science data (or a derivative of it) and a memory buffer+lag correlator at the antenna is used to measure the delay. The 1PPS (locked to the array timing reference) at the correlator site is encoded into the return signal and negatively delayed by the measured TL delay such that it is ~aligned in time to the 1PPS source. Automatic correction for the science data digital delay, using the (antenna) 1PPS (resampled into the *cLO* clock domain), as is currently done in the WIDAR correlator, is then performed. (2) The delay is measured via round-trip as mentioned and then introduced as a delay term in the re-sampler circuit of Figure 4. This has the effect of "collecting photons at the antenna and delay-correcting them to the correlator site". (3) A GPS receiver at each antenna injects its 1PPS into the digitized science data for transmission to the correlator site.

Further Work

Initial modelling and theory indicates that this method looks promising. A simple MathCad model of tracer phase measurement using digital tone extraction on a digital sine-wave was built and tested for the example shown, including introducing some fiber and CDR-introduced tracer phase jitter. Digital re-sampling (Figure 4) has been extensively modelled for the NRC 'TALON' SKA1 Mid correlator/beamformer project including a method to randomize any spectral spurs this circuit produces, as well as initial implementation in an FPGA and Modelsim-tested against a MatLab model of the same. Still, a real hardware demonstrator is required to determine feasibility. NRC plans on embarking on construction of a lab demonstrator of this method using a Xilinx demo board in the fall of 2018. Discussions with the NRAO have started on the possibility of development and construction of an on-sky demonstrator, connecting the VLBA Pie Town antenna into the JVLA WIDAR correlator. At this point it is believed that this demonstrator can be built with little or no custom hardware development potentially using a COTS Xilinx RFSoC board and an NRC TALON-DX FPGA board with an Intel Stratix-10 FPGA and 64 fiber SERDES up to 26G ea.

References

[1] Carlson, B., Gunaratne, T., *Signal processing Aspects of the Sample Clock Frequency Offset Scheme for the SKA1 Mid Telescope Array*, 32nd URSI GASS, Montreal, 19-26 August 2017.

[2] Carlson, B.R., *Incoherent clocking in coherent radio interferometers*, IEE Electronics Letters, DOI 10.1049/el.2018.0964 (accepted manuscript, on-line @ https://goo.gl/hun6ni as of May 24, 2018).

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