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A Minimum Sufficient Station Processing System for LOFAR or SKA

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Abstract

It seems possible to design and build a '*minimum but sufficient*' hardware system for a LOFAR station. This means that it can reasonably be expected that all the remaining development in beamformig and RFI mitigation can be done in software, while the hardware will not have to be modified during the lifetime of LOFAR.

Contents

1 Introduction

LOFAR has been called the first 'software radio telescope'. However, there will still be a substantial amount of special-purpose signal processing hardware, most of which will be in the stations. Its main features are reasonably clear by now [1], but substantial (and time-consuming) development is still needed in the areas of beam-forming and RFI mitigation. Under those conditions it seems difficult to have a LOFAR prototype station operational by the end of 2002, unless it is possible to define the station hardware system in such a way that all the remaining development can be done in software. Hardware and software have roughly the same lead-time, but if the software is properly designed it is far easier and cheaper to modify.

This document makes the case that it is possible in this stage to design and build a *minimum but suffient* station hardware system, which would probably not have to be changed substantially during the lifetime of LOFAR. The development of the necessary algorithms can then be done under realistic conditions, using the prototype LOFAR station.

2 Requirements and tentative block diagram

We will not concern ourselves here with the conversion of e.m. radiation into voltage, but take the signals from the point they emerge from the active antennas. A minimum but sufficient station *hardware* system must then meet the following requirements (see also [1] [2]):

- The signal from each dipole must be split into 'monochromatic' (1 kHz) channels. This is expected by the correlator (FX), and also makes it
- The channels are within an arbitrarily selectable set of sub-bands.
- The above implies D/A conversion. The expected RFI dynamic range requires 14 bits
- All beam conditioning (except dipole addition) is done by means of a *single* real-time complex multiplication per channel. This includes pointing, tracking, tapering, nulling etc. See section 3.
- The complex multiplication coefficients are calculated by the station processor. In addition to deterministic control parameters for (sub-)band selection, pointing and tracking, the direction of known RFI sources etc, it .requires the following *feed-back* information for adaptive nulling:
  - The individual channel signals, after the multiplication.
  - The individual beam output signals, i.e. after the addition.
  - Other...?
- After beamforming (by simple addition), the number of bits can be reduced to 4 because all signals above the noise are assumed to have been removed at this point.

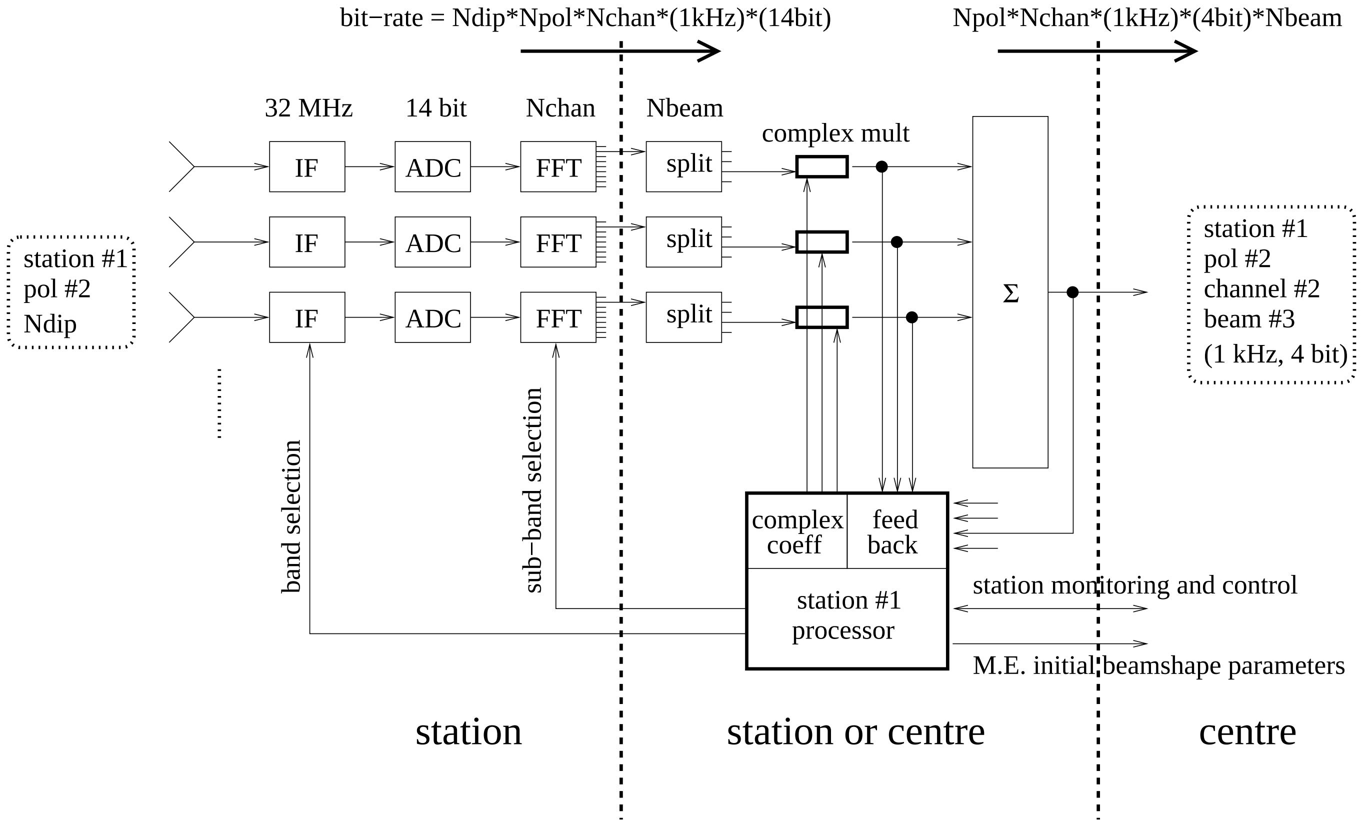

Figure 1: *Block diagram of a minimum but sufficient processing system for a LOFAR station. All beam conditioning (pointing, tracking, tapering, nulling etc) is applied by means of a single complex multiplication per beam. The multiplication coefficients are calculated by the station processor. Whereas the algorithms do not have to be specified in detail yet, it is important to make sure that the input information as indicated in the diagram will be sufficient for 'all'algorithms that will be developed for LOFAR stations.*

These requirements can be translated into the block diagram of fig 1. Note that the station processor does not have to be at the station itself, but the transmission bit-rate is higher if it is located at the LOFAR centre. The break-even point would be at :

$$N_{beam} > N_{dip} \times (14/4) \approx 3500 \qquad (1)$$

which is an unrealistically high number of beams. However, there might still be reasons for transmitting the individual dipole signals, e.g. for the LOFAR core stations. The important thing is that both options are possible.

The **big question** is whether the feed-back information is sufficient for all the operations we will be able to think of during the life-time of LOFAR, especially for adaptive nulling.

3 A single complex multiplication

One of the assumptions of the proposed system is that only a *single* complex multiplication needs to be implemented for each (mono-chromatic) channel. The multiplication coefficient is a *product* of the following complex components:

- **[Active antenna correction]**. In some systems (e.g. a class of SKA tiiles), the 'active' antenna causes a highly frequency-dependent complex factor (mostly phase?), which can only be tolerated if they can be corrected, i.e. if they can either be predicted or measured.
- **Pointing, including tracking**. These are linear phase gradients over the station, calculated deterministically from the dipole positions w.r.t. to the station phase centre, and the sky coordinates (RA/DEC) of the field centre. NB:The station beams must (smoothly) track the sky during observations. This is necessary to minimise source distortion in residual images, i.e. those faint and or extended sources that are not in the Sky Model and can therefore not be subtracted from the the uv-data.
- **Tapering**, i.e. applying frequency-dependent dipole weights. This reduces the beam sidelobes, which is very desirable. It also increases the beamwidth in order to see more bright calibrator sources (calibratability, see [3]).
- **Nulling** of RFI sources, and very bright astronomical sources like Cas A. This operation can *always* be seen as the linear combination of the nominal station beam, with another beam pointed at the RFI source. Or in other words, as the addition of the dipole signals with two different sets of coefficients. This is why the multiplication *must be followed by an addition,* as in our block diagram.
- **Other ... ?**

Nulling can be either deterministic or adaptive, depending on whether the RFI source is in a known direction. It should be realised that the depth of a deterministic null, and the effect of tapering on the beam-shape, will be affected by subsequent adaptive nulling.

The multiplication will have a finite resolution, depending on its implementation. An accuracy of about 1% (i.e. 0.5 deg) is probably sufficient, and even that might be relaxed. The update rate of the coefficient values is (probably) determined by the tracking of the sky. Assuming a maximum sky velocity of $10^{-4} rad/s$ (i.e. 15 deg/h) and a station size of 100 m, the maximum phase variation (for $\lambda = 2m$) is about 0.1 deg/s. Thus, an update rate of once every few seconds will be adequate.

4 Adaptive nulling

As mentioned in section 3, directional nulling can be seen as the linear combination of the nominal station beam with other beams pointed at RFI sources, in such a way that the response in the direction of the RFI is minimised. If the direction (and frequency-signature) of the RFI sources is known, the relevant coefficients can in principle be calculated from the station parameters. In practice, the quality (depth) of the nulls is reduced because of imprecise knowledge of instrumental effects like electronic phase and gain, or coupling between dipoles.

A much more attractive possibility is adaptive nulling, where the coefficients are determined from the signals themselves, and *a priori* knowledge of RFI sources is not necessarily required (although it usually helps). This is somewhat analogous to self-calibration, which is also a closed-loop method, and much more effective than open-loop calibration. Adaptive nulling has the following main elements:

- Some **criterion** to measure the effectiveness of the nulls. One way is to minimise the output power per beam, integrated over some interval. As fig 2 illustrates, the power will be minimised if all signals that stick above the noise have been removed. Another way is to measure the correlation between the outputs of beams that are pointing in different directions. The latter assumes that RFI is entering via the sidelobes, and that the correlation is greatest when one of the beams is pointed in its direction (see also fig 3).
- An **algorithm** to determine optimal values for the coefficients. Trial and error schemes like 'genetic' algorithms may be used to derive coefficients from beam output powers. The problem is that, since power measurement is a non-linear operation, a separate integration is needed for each trial set of coefficients. It is probably more efficient to use the cross-correlation information, from which improved coefficients can readily be estimated, perhaps even by inversion.
- **Constraints** on the possible values of the (set of) coefficients. In its simplest form this avoids the 'solution' where all coefficients are zero. But constraints are also necessary to ensure that the resulting station beam alsways has a 'reasonable' pointing centre, peak response and sidelobe level. It is also important that beamshape variations in time and frequency are 'smooth'. The latter minimises the number of parameters needed to characterize a beam, which is important for calibration (see section 5 and [3]).

The sensitivity can be increased by integrating longer, provided that all relevant parameters remain constant over the integration interval. This will not be the case for RFI transients. The integration time will also be limited by the fact that the RFI source will usually not be stationary w.r.t. the beam that is pointing at it.

The sensitivity will be maximum for RFI signals that have a bandwidth close to the channel bandwidth (1 kHz). The narrow band separates man-made RFI from astronomical sources.

5 Beamshape characterization for the M.E.

The parametrized 'shape' of LOFAR station beams is part of the so-called Measurement Equation (M.E.). In order to achieve the projected dynamic range of up to 10^7 , the M.E. parameter values have to be estimated

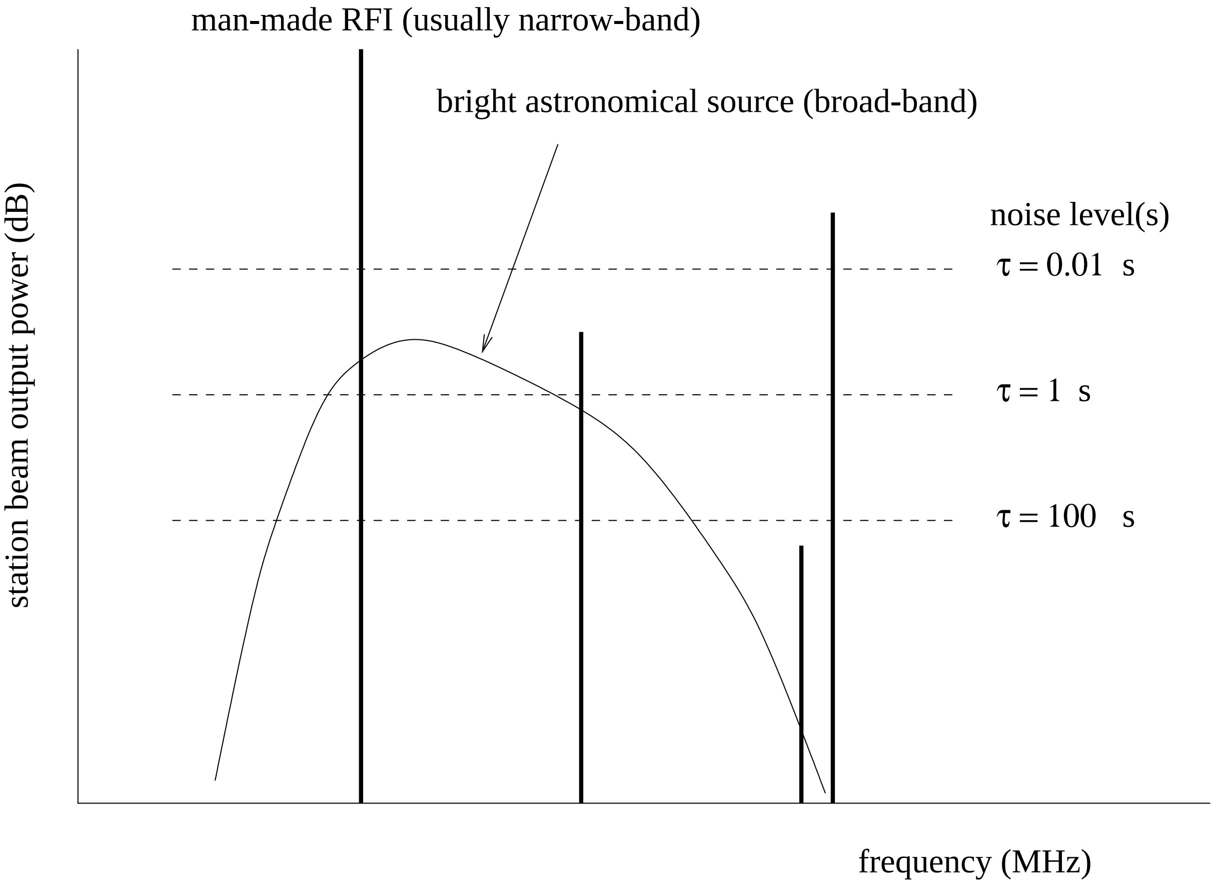

Figure 2: *Adaptive RFI mitigation techniques can only detect RFI (and astronomical) sources that stick out above the noise. A criterion for successful nulling is that the ouput power of a station beam is minimised to the noise level.*

with high accuracy. Whereas the final values will be obtained iteratively by means of 'station-core' and 'station-station' self-calibration (selfcal), the station processor is required to provide approximate initial values. It is also required to make sure that the station beams are formed in such a way that they are as 'smooth' as possible in all dimensions.

Calibratability requires that a station (voltage) beam is characterised by a minimum number of parameters. First of all there are the spatial parameters, of which there should be less then $N/2$, where N is the number of LOFAR stations. Roughly half of these are available to describe the main lobe analytically, and the other half for describing the side-lobes at the positions of the brightest sources. Fortunately, the main lobe is guaranteed to be smooth because it is formed by a band-limited FFT (i.e. the dipoles are relatively close together).

Each beamshape parameter will vary in frequency and time. These variations should be as smooth as possible, so that they can be described by low-order polynomials in frequency and time. The latter are the actual M.E. parameters that are estimated by selfcal. The station processor has control over the smoothness by constraining the solutions for beam-forming coefficients.

Finally, the station processor needs a few recipes to measure station beams by scanning (rapidly) across the brightest calibrator sources, or possibly an artificial source on a high pole (a sort of near-field scanner).

6 Conclusions

It seems possible to design and build a 'minimum but sufficient' hardware system for a LOFAR station, which will not have to be modified as a result of evolving algorithms. However, the assertion that the feedback information to the station processor, as indicated in the block diagram in fig 1, is sufficient should be vigorously challenged before we start building.

Acknowledgements

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References

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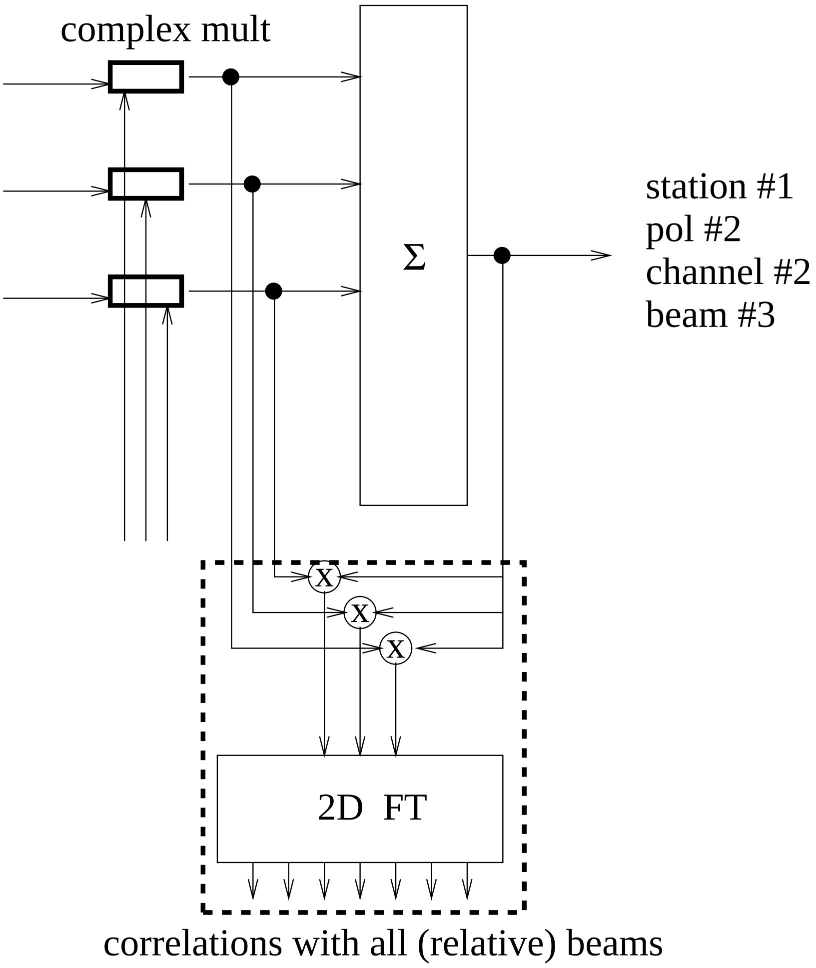

Figure 3: *A closed-loop method to remove RFI is to correlate the output of each station beam with the outputs of all its other beams. The results can be used to estimate improved beam-forming coefficients to null out RFI. This is equivalent to adding the beam that is pointing at the RFI source to the 'tracking' beam, in such a way that the RFI that enters via a sidelobe of the tracking beam is eliminated. The actual correlation may either be done in software, or by means of a special hardware unit (dashed box). The indicated scheme is equivalent to correlating beams, and demonstrates that various implementations are possible.*