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FUTURE DEVELOPMENTS AND ENERGY MANAGEMENT: AN ANALOG POINT OF VIEW

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Abstract. Antenna arrays overcome single dishes limitations at a high energetical price. Analog based solutions for energy efficiency are presented, with the general concept of an adaptative instrument.

Keywords: energy, radiotelescope, array, electronics, RF, analog, frontend

1 Introduction

While single dishes are limited by both mechanical aspect and the fundamental diffraction limit, antenna arrays theoretically break those limitations, giving access to survey speed, but it implies lots of instrumented channels with a corresponding financial and energetical cost. The effective access to FoV is conditionned by the ability of computing enough array beams inside the single element FoV. There is thus a new practical feasability limit which is essentially linked to electronics and computing costs.Given the quest for ever better performances on one hand, and the global energetical and financial world context on the other hand, there is obviously a need for making those instruments more sober if one wants to see them built and operated succesfuly. In this context, the emphasis on operating cost reduction for phase I in the SKA Observatory Development Program (SODP) [SKA observatory (2021)] is not surprising. Several margins for improvements are identified in the following, ranging from low level electronics to global optimization of the instrument, with an important potential impact on digital backends consumption.

2 Energy consumption on aperture arrays

2.1 Some definitions

The *frontend* part consists in RF instrumentation at the antenna scale. The *station backend* part at the station scale, consists in digitization, channelizing and beamforming. The *central backend* part at the full array scale, consists in correlation and imaging features. The first 2 parts are generally on site while the central backend is centralized off site.

2.2 SKA I low numbers

SKA I Low is 58% of 1 km^2 in size: 512 stations with 256 antennas, 38 m diameter each, for a total of 131072 antennas over 578000 m^2. On-site consumption is expected at 3.3 MW (frontend + station backend), it represents an electricity cost of 5.2 Meuros per year and some thousands of CO2 tons. While the SKA projections don't separate frontend and station backend, an educated guess would be about 0.35 MW for frontend (1.35W/channel) and 2.95 MW for station backend (11W/channel). Off-site science processing centre (SPC) account for an additional 1.9 MW. The total consumption for SKA I low would then be 5.2 MW, with a share of 7% from frontend, 57% from station backend, and 36% for central backend. A consumption of 3.3 MW on site is about the dimensionning of a diesel train engine, which is technically feasible but expensive and not straightforward on a remote site. Despite some solar panels, there will be some MW dissipated through diesel generators each night and part of the day in support, with a corresponding high electricity bill and carbon emissions. The share could be different in other frequency bands, which is discussed in the following section.

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2.3 Power consumption vs. frequency

A simple toy model is used where antennas are positionned on a regular grid of periodicity $lambda2$, λ being the observation wavelength. Each antenna is fitted with 2 electronic channels dissipating 1W each. The density of antennas per unit surface is $\frac{4}{\lambda^2}$, the density of electronic channels is twice. With 1 W per channel, we thus have a density of dissipated power P_{surf} in W/m^2 expressed as $P_{surf} = \frac{8}{\lambda^2}$. At 100 MHz $P_{surf} \approx 1$ W/m^2, a 1 km^2 geometrical aperture has a total power consumption of the order of 1 MW. At 1 GHz, $P_{surf} \approx 100$ W/m^2 and the kilometer square total power is of the order of 100 MW. That's about the dimensioning of a transatlantic liner engine, once again technically feasible, but representing a financial and logistical nightmare for a radiotelescope, which concretely prevents it to be built. Nevertheless important progresses have been made with respect to that baseline estimation, with microelectronics development in Nançay allowing to reduce this consumption by a factor of 4. There are several possibilities to decrease it further, down to a more reasonable range of less than 10 MW, as will be shown in the following sections.

2.4 Power consumption on existing/projected instruments

The power consumption per surface for LOFAR LBA and HBA, SKA I low and Nenufar are summed up in figure 1 for both analog frontend (dots) and station backend (crosses). The quadratical trend in frequency is well followed by frontend systems, with SKA I low being above the 1W/channel reference essentially because of design choices like optical conversion included in the frontend. The Nenufar frontend is also above that reference, but it includes analog beamforming features: groups of 19 antennas are beamformed analogically before digitization as a single channel. The corresponding reduction of digitizing need can been seen in the figure of Nenufar's backend consumption, which is only about 0.02 W/m^2 with respect to the area effectively covered by a single digital channel. The effective consumption per digitized channel is around 5W, but the antennas grouping decrease it to an apparent $5/19 = 0.26$ W/antenna. The same effect can be seen on LOFAR HBA figures, with higher consumption on older technologies following the progress made in computing energy efficiency in the last decade.[TOP500 project team (2021)] Antennas grouping with analog beamforming is here a first example of a possible analog design choice having substantial impact on the digital part and the overall energy consumption. It comes to the price of reducing the field of view, but this loss may be recovered at low energetical price as will be shown in the following.

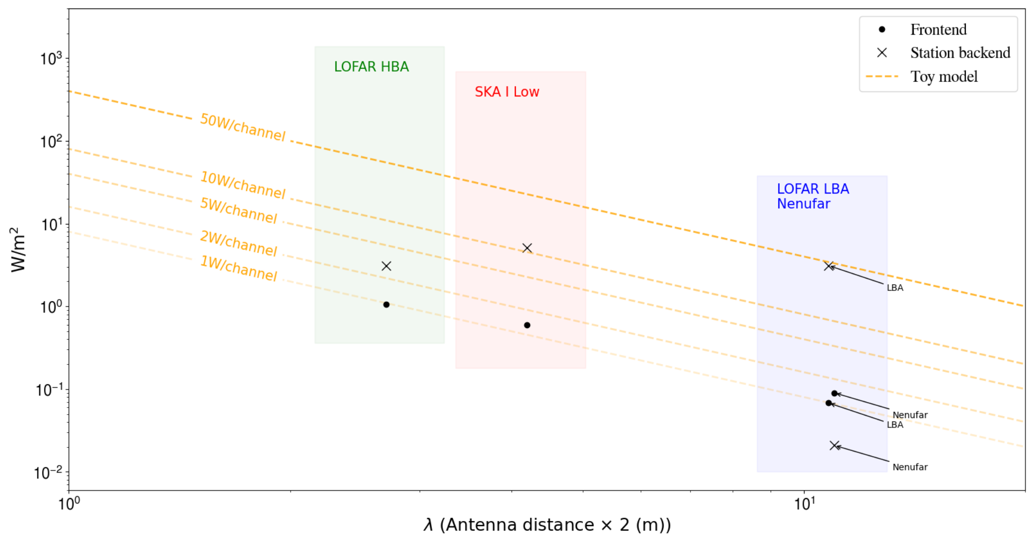

Fig. 1. Power consumption per instrumented meter square as a function of average distance between antennas, for both analog frontend (dots) and station backend (crosses), on LOFAR LBA (10 - 100 MHz) and HBA (120-240 MHz), SKA I low (50 - 350 MHz) and Nenufar (10-100 MHz). The orange dashed line is the toy model at 1 W/channel presented in section 2.3

3 Analog solutions for energy management

3.1 Integrated circuits optimization

Including energy consumption as yet another specification is pulling the R&D work towards energy optimized solutions, as can be illustrated by the work done in Nançay within the framework of the Aperture Array Integrated Receiver project (AAIR), focusing on GHz dense aperture array. The GHz scale implies 100 MW power scale (see 2.3) for 1 km^2, which makes it practically not feasible. Nevertheless this band is particularly important given the HI line, and GHz aperture arrays would unlock survey speeds 3 to 10 times higher than SKAmid dishes [Wijnholds & Jongerius (2013)]. The motto behind aperture array for SKA mid frequencies was "the billion galaxies survey machine", this band has thus pulled several efforts toward power consumption reduction. The EMBRACE demonstrator [Torchinsky et al. (2016)] was a $64m^2$/4608 antennas dense aperture array, operating succesfuly between 500 MHz and 1.5 GHz from 2011 to 2017 in Nançay. Its integrated analog frontend has been designed in Nançay, including low noise amplifier (LNA), signal conditioning and analog beamforming through integrated beamformer chips. The power consumption was 1.2 W/channel, and has been decreased to 300 mW/channel 6 years after with further optimizations on a new AAIR prototype tile. This brings a GHz km^2 aperture array to a 25 MW power consumption scale. An additional factor of 2 reduction should be straightforward, bringing a km^2 down to 10 MW. Additional optimizations at the whole instrument scale are needed to really make it an energy efficient system, as will be presented in following sections.

3.2 Analog/digital load balance

Analog based solutions may also have an impact on the consumption of the digital part. In the simplest example, digitizing a group of beamformed antennas is paid in reduction of the FoV, but this FoV loss can be recovered at a marginal cost by adding more analog beams. The splitting of the RF signal several times allows to get several independent beams in parallel. This solution has already been demonstrated on several applications, and has a big impact on the main power sink for systems like SKA I low, namely the station backend. Analog beamforming may be seen as a pre processing stage reducing the burden on the following digital stages. It may also have a radical impact on the central backend, as illustrated in a study [Wijnholds & Jongerius (2013)] considering 2 scenarii for a full 1 km^2 SKA low : "AA low" with 911 stations of diameter 35m (about 250 antennas), and "alternative AA low" with 280 stations of diameter 75m (about 1000 antennas). The larger stations in the alternative scenario implies a FoV loss, which is recovered by generating 4 beams. We thus have 2 equivalent systems with respect to performances. Results show beamforming requirements are logically quadrupled. An analog beamforming system would accomodate those 4 beams without problems. Most impressively requirements on imaging as a whole are reduced by a factor ≈ 250. The AA low original scenario would dissipate 8.5 MW for imaging, while the alternative scenario only dissipates 34 kW. This is mainly due to the fact that imaging computing power requirements (taking into account w-projection only)[Cornwell et al. (2012)][Perley & Clark (2003)] falls like D_s^{-4} as the station diameter D_s increases, and like N_s^2 as the number of stations N_s decreases, while it scales linearly with respect to the number of RF analog beams. There is thus an enormous potential for power reduction on the whole chain working with analog beamforming. The SKA observatory (SKAO) has settled the design of SKA I low somewhere between the two scenarii presented here, with 512 stations of 256 antennas each and no analog beamforming. It should be noted however that RF channel splitting allows for instrument upgrade without major modifications, some additional instrumentation being installed for more independent RF channels. Also if the remaining 40% surface for a full km^2 is to be installed, their positions may be determined with those optimizations in mind.

3.3 RFI and input dynamics

Input dynamics has the biggest influence on frontend consumption, and it is dimensionned with respect to the maximum emission on site, instruments are thus systematically designed for a maximum frontend consumption. The maximum dynamic range of incoming RFI is most often around 6 orders of magnitude or more, implying 14 bits or so digitization, whereas a few bits may be sufficient to describe the astrophysical signal, and frontend electronics having to run in a regime dissipating up to ten times more than with a minimal input dynamics. There is thus an interest in mitigating the strongest RFIs on site *before* the digitization step, formitigating nonlinear intermodulation effects which are not correctible after digitization, reducing the required coding depth, and the frontend power consumption. Several methods for RFI mitigation already exist, but their digital nature and/or lack of automatization makes them unable to scale at SKA level. We thus need an almost autonomous system, with low energetical consumption, that could both detect and mitigate the strongest RFI signals analogically. For SKA we also add the constraint that additional features should be added to the existing instrumentation without deep modifications. The best instrument for RFI detection being the scientific instrument itself, one can design additional RF analog beams that are dedicated to RFI detection. Splitting the analog signal at each antenna, we create an additional RF channel, then beamformed analogically, with a pointing direction that may be updated regularly, so that a RFI dedicated beam scans the sky in parallel to the main astrophysical channel. In SKA I low, this can be done in existing "smart box" gathering signals from 16 antennas, giving a $\approx$ 20 degrees FWHM beam. With such a resolution, and a 1 ms integration time (sufficient for the biggest emissions), the whole sky can be scanned in 200 ms by regularly updating the beamforming weights. Since independent from the science beam, the RFI dedicated beam may have specific settings for RFI detection, e.g. a larger input dynamics and lower sensitivity. When an emission at a given beam pointing is found to be above a pre determined threshold, the RFI dedicated beam is fixed on target, and the RFI signal may be re injected out of phase in the main astrophysical path. That way the RFI emissions is mitigated in the analog part, keeping the input dynamics requirements in a reasonable range. The simplicity, autonomy and low consumption constraints are met thanks to integration of an almost closed loop analog system with a simple thresholding scheme. Several analog beams dedicated to RFIs may be generated, so that multiple source can be corrected for for in parallel.

3.4 Adaptive instrument

Designing electronics is basically defining a set of components, their values and the connections between them. If the circuit connections are defined, and the value of each component is a free parameter, meeting the specifications means optimizing a given cost function (aggregating specifications and constraints) with respect to all those free parameters. Through controllable integrated components receiving digital commands on a few bits, one may thus design a kind of programmable, or configurable frontend electronics, with free parameters being values for several active sources and impedances throughout the circuit. This is the heart of the Smart-AAIR project following AAIR, with the goal of optmizing a cost/perfomance ratio, by dynamically considering a set of specifications for each observation or each type of observations, thus using only the necessary resources for a given goal. This implies to model the complex relations between low level parameters at the electronic board level (impedances, voltages, currents) and high level parameters (sensitivity, dynamics, power consumption), with high dimensionnality and non linearities, and simulations being difficult and very time consuming on some parameters like input dynamics. Since we want dynamic modeling, we need a solution for measurement based, accurate and fast modeling of that relation, both for direct modeling (getting the performances associated with a set of low level parameters) and inverse modeling (getting the optimal low level parameters with respect to given performance goals). Machine learning is particularly suited to those constraints and we already tested the use of neural networks in Nançay, the first stage being a validation on simulated data. [Censier & Bosse (2020)]. Relatively small networks are showned to be sufficiently accurate (at the 0.1 dB level or less) for both direct and inverse modeling, with execution times ranging from microseconds to milliseconds on an unoptimized laptop where simulations may take days. This opens the possibility for dynamic modeling without any prior hypothesis, and optimizing low level parameters with respect to both performances goals and environmental constraints like energy provision and RFI. This concept thus has a link with all the sections above, for example, some RFI dedicated beam(s) (see section 3.3) would be a rich source of dynamic informations about the electromagnetic environment, and could be taken into account in the optimization. We are currently setting up a measurement bench for training the network directly on measured data, using a S-AAIR prototype board with 8 controllable low level parameters.

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