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Embedded Processing Applications

RSP Firmware
Functional Specification

Verified:			
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Table of contents

1 Introduction

1.1 Purpose of this document

The purpose of this document is to specify the functionality of the embedded processing applications for the LOFAR remote station. It can be used both as input for implementation, and for estimation of the hardware demands.

1.2 Scope

The primary focus of the document is the digital signal processing functions. Interfaces with other systems are only briefly identified here, but references are given to the appropriate documents in which they are specified in more detail.

1.3 Overview

This document has been structure in the following way. First the context of the RSP subsystem and its interfaces to other subsystems are described in section 2.1. Then sections 2.2 and 2.3 describe the main data processing and the main control functions, respectively. Section 2.4 addresses the testing of the RSP firmware. Finally, chapter 3 specifies the data processing functions in detail.

1.3.1 Applicable documents

No.	Document Number	Issue/rev	Title
AD.1	LOFAR-ASTRON-ADD-007	1.0	Station Digital Processing Architectural Design Document
AD.2	LOFAR-ASTRON-SRS-001	1.0	Remote Station Subsystem Requirements Specification
AD.3	LOFAR-ASTRON-SRS-003	2.0	Station Digital Processing Requirements
AD.4	LOFAR-ASTRON-DOC-006	0.4	Algorithm Theoretical Baseline

1.3.2 Referenced documents

No.	Document Number	Issue/rev	Title
RD.1	LOFAR-ASTRON-MEM-082	0.6	Distributed Beam Forming Alternative
RD.2	LOFAR-ASTRON-ADD-007	1.0	Station Digital Processing Architectural Design Document
RD.3	LOFAR-ASTRON-SDD-035	1.0	Functional Specification of the RSP board diagnostics.
RD.4	LOFAR-ASTRON-SDD-031	1.1	Functional Specification Station Remote Update and Configuration
RD.5	LOFAR-ASTRON-ICD-002	6.0	RSP-MAC Interface Description
RD.6	LOFAR-ASTRON-ICD-009	3.0	RSP-CEP Interface Description
RD.7	LOFAR-ASTRON-MEM-162	1.0	LOFAR Digital Filter Requirements
RD.8	LOFAR-ASTRON-MEM-129	1.0	Quantization Error Analysis of Digital Signal

			Processing Blocks
RD.9	LOFAR-ASTRON-MEM-185	2.0	Test Strategy for the RSP firmware
RD.10	LOFAR-ASTRON-MEM-186	2.0	Test Specification for the RSP firmware
RD.11	LOFAR-ASTRON-SDD-018	3.0	RSP Firmware Design Description

1.3.3 Terminology

Term	Definitions
TBB	Transient Buffer Board
LCU	Local Control Unit
MAC	Monitoring and Control subsystem
CEP	Central Processing Subsystem
subband	1/512-th of the input spectrum
beamlet	A small beam, spanning one subband.
crosslet	A source for cross correlation, spanning one subband of a particular antenna.
RSP	Remote Station Processing
HBA	High Band Antenna
RCU	Receiver Unit
TDS	Timing Distribution for Subrack

2 Functional Specifications

2.1 Context

The digital processing application is implemented as firmware running on the RSP board. The system context of the firmware is depicted in Figure 1.

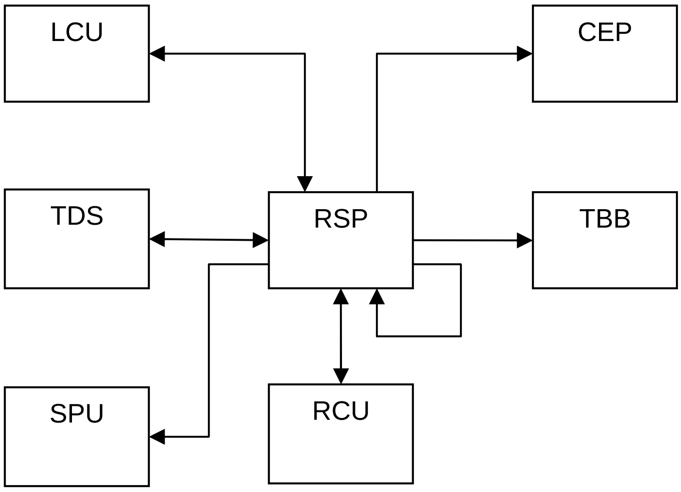

Figure 1: System context for the RSP firmware

The main function of the RSP firmware is to process signal data that is received by the receiver unit (RCU). Because the processing function is distributed among several RSP boards, there is a data interface between RSP boards. The processed data is sent to the Central Processor (CEP). For transient recording, the RCU data is forwarded through RSP towards the Transient Buffer Board (TBB). A Timing Distribution board for Subrack (TDS) provides the system clock and synchronization signal. A local control unit (LCU) issues monitoring and control commands to RSP, and uses the RSP as a gateway for monitoring and controlling a Subrack Power Unit (SPU), and also RCU and TDS.

For the interface between RSP and LCU, see RD.5. For the interface between RSP and CEP, see RD.6. The interfaces are specified by the respective subsystems.

In general, the RSP performs a combination of data processing functions and control functions. These functions are specified in detail in the following sections. The RSP firmware design is described in [RD.11].

2.2 Data processing functions

Data that is exchanged between processing units will be sent as frames, and labelled with a timestamp.

2.2.1 Synchronization of data processing

All operations that are performed on the data shall be fully synchronized, using an external synchronization signal (pps). Data that is exchanged between RSP boards and data that is sent to CEP shall be labelled using a timestamp, in order to ensure the data processing of the various sub systems is synchronized.

2.2.2 Delay compensation

RSP shall support time delay compensation of the RCU antenna inputs, in order to compensate for the cable lengths. Delay compensation can be done both in time domain as well as in frequency domain. The time domain correction has a resolution of 1 sample, and a maximum range of 128 samples. Fractional delay compensation is supported using phase adjustments in the frequency domain (see 2.2.9).

2.2.3 DC blocking

Low frequency signals in the input shall be blocked using a simple high pass filter. The cut-off frequency is < 1 MHz. This filter can be switched on or off when needed.

2.2.4 Spectral inversion

RSP shall support spectral inversion of the input data, in order to correct the input data in case of 2nd Nyquist sampling. This shall be implemented by negating every 2nd sample.

2.2.5 Subband separation

The wideband input signal (80 or 100 MHz bandwidth) shall be separated into 512 small subbands of 156.25 kHz or 195.3125 kHz bandwidth. The out-of-band rejection of a subband shall be more than 80 dB. The subband separation shall be performed using a polyphase prefilter, followed by a fast fourier transform. The filter requirements for the subband separation are specified in RD.6. In summary, the requirements for the subband filters are:

- The ripple in the passband shall be 0.5 dB or less.
- The transition region between pass band and stopband shall not exceed the width of one subband.
- The stopband attenuation at 1 subband distance from the passband edge shall be at least 80 dB.
- Further away from the passband edge, the stopband attenuation shall increase.

Also, it shall be possible to reconstruct the time-series data using the frequency data (near-perfect reconstruction).

A filter set that complies with these requirements has been computed, the characteristics of this filter are shown in Figure 2 - Figure 4.

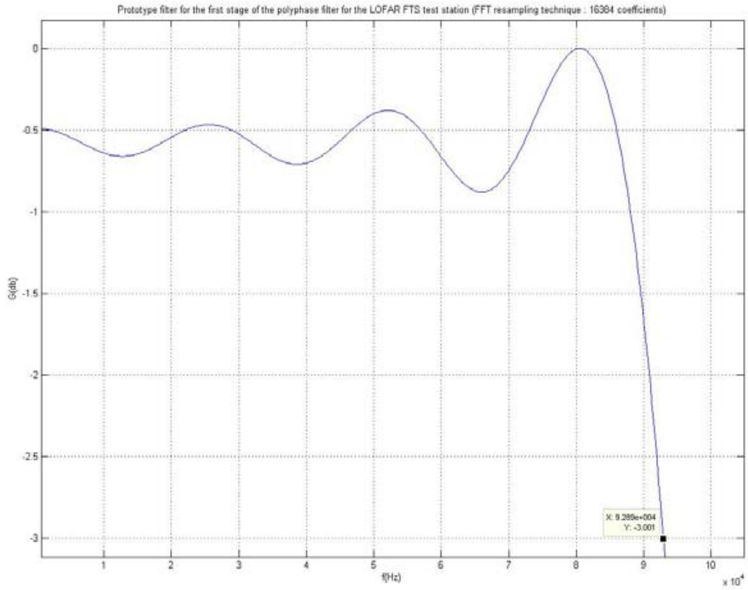

Figure 2: Passband of the subband filter.

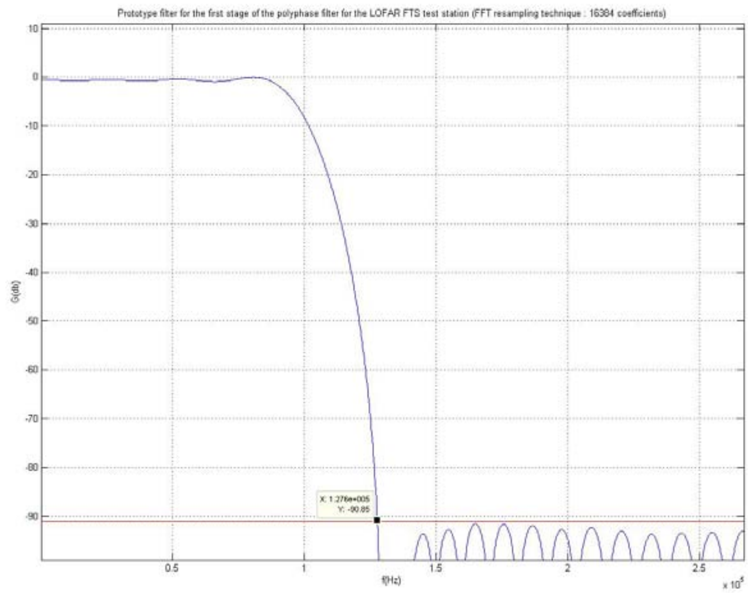

Figure 3: Transition band of the subband filter.

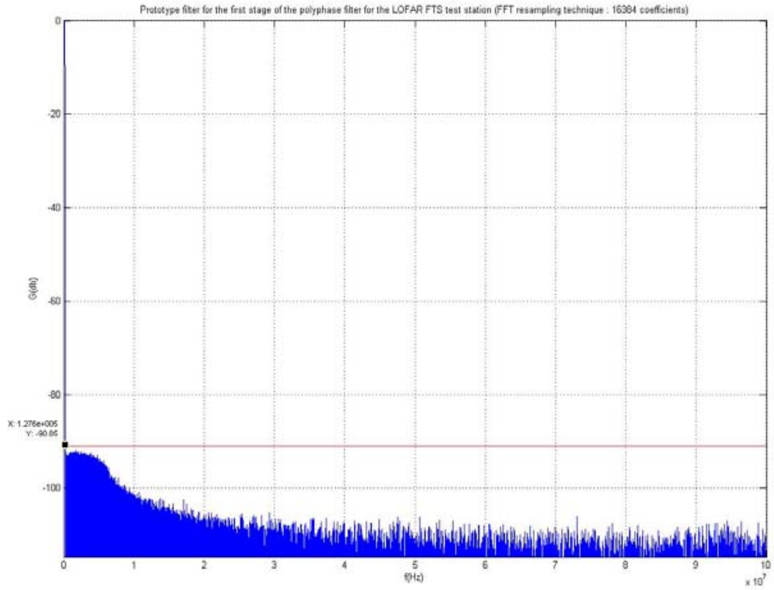

Figure 4: Stopband of the subband filter.

2.2.6 Station beam forming

Station beam forming shall be implemented using spectral separation into subbands (see 2.2.5), followed by a phase / amplitude adjustment (see 2.2.9) of a number of beamlet (see 2.2.9) and addition of the beamlet data for all antenna's. The total output bandwidth shall be at least 32 MHz. This corresponds to 205 beamlets at 160 MHz sample rate, and 164 beamlets at 200 MHz sample rate.

2.2.7 Subband statistics

For system health monitoring purposes, the power in each subband shall be calculated for each update interval.

2.2.8 Beamlet allocation

RSP shall provide up to 216 beamlets: narrow beams, spanning a single subband. The beamlets can be individually allocated to a specific frequency (subband selection). The beamlets are dual polarized, but because the subband for each polarization can be allocated separately, the number of available beams is effectively doubled when only a single polarization output is required. The number of beamlets that is sent to CEP is configurable.

2.2.9 Beamlet transformation

RSP shall support phase and amplitude corrections for each beamlet using a fully parameterizable linear transformation. This transformation is defined as:

$$\begin{bmatrix} x'_r \\ x'_i \\ y'_r \\ y'_i \end{bmatrix} = \begin{bmatrix} a_{1,1} & a_{1,2} & a_{1,3} & a_{1,4} \\ a_{2,1} & a_{2,2} & a_{2,3} & a_{2,4} \\ a_{3,1} & a_{3,2} & a_{3,3} & a_{3,4} \\ a_{4,1} & a_{4,2} & a_{3,4} & a_{4,4} \end{bmatrix} \cdot \begin{bmatrix} x_r \\ x_i \\ y_r \\ y_i \end{bmatrix}$$

Where x_r and x_i are the real and imaginary parts of the x polarization input (similar for y). The beamforming coefficients $a_{i,j}$ are individually configurable for each antenna input.

2.2.10 Beamlet statistics

In order to enable local monitoring of the beam quality, the power in each beamlet shall be calculated for each update interval.

2.2.11 Orthogonalization of polarizations

RSP shall support orthogonalization of the polarizations using the beamlet transformation function of section 2.2.9. Using zero for the appropriate beamforming coefficients $a_{i,j}$ disables the orthogonalization.

2.2.12 Sub arraying

RSP supports sub arraying (using only part of the antennas to form a single beam) as long as the total output bandwidth is limited to 216 beamlets and as long as all sub arrays use the same sample rate.

2.2.13 Beam switching

RSP supports switching of the beam direction or frequency, once for each update interval.

2.2.14 Cross correlation

RSP shall perform calculation of cross correlation of subband data between all antennas (Full N x N array correlation matrix). For each antenna, two subbands can be selected for correlation. These are denoted as a crosslets. The crosslets of each antenna will be correlated with the crosslets of all other antenna's (cross correlation of polarizations is included). The total accumulative number of crosslets is the number of crosslets per antenna times the number of antennas, so 2N=192 when N=96 antennas.

2.2.15 Station calibration

Calibration is required to correct for phase and amplitude distortions in antenna cables and equipment. RSP facilitates calibration in two ways:

- The cross correlation function (see 2.2.14) can be used to provide input to the calibration algorithm.
- The beamlet transformation (see 2.2.8) can be used to apply the phase and amplitude corrections.

Note the calibration algorithm itself is not part of the RSP firmware.

2.2.16 RFI mitigation

RFI mitigation is used to suppress unwanted signals. It can be done spectrally, spatially and in the time domain. RFI mitigation algorithms are not part of the RSP firmware. RSP facilitates the following RFI mitigation algorithms:

- Detection of RFI, and estimating the direction of arrival is supported using the subband statistics and cross correlation statistics.
- Spectral RFI mitigation (blanking those parts in the spectrum that are contaminated with strong RFI signals) is supported by not selecting these subbands for the beam forming.
- Spatial RFI mitigation (nulling) is supported by adapting the shape of the beam, using the beam forming coefficients.
- Time domain RFI excision is supported up to a resolution of 1 second (limited by the update interval rate).

2.2.17 Transients

Detection and storage of transient phenomena is done on a separate transient buffer board (TBB). The RSP firmware shall forward either the raw antenna data or subband separated data towards the TBB.

2.3 Control functions

2.3.1 Monitoring and control

RSP shall support monitoring and control of all its functions through the RSP-MAC interface [RD.5]. This includes selection of the subbands used for beam forming, setting of the beam forming coefficients, read-out of various statistics, etc. The update interval for the monitoring and control data is 1 second.

2.3.2 Synchronized control

All monitoring and control operations shall be synchronized using the external synchronization signal (pps). Because the internal signal processing functions introduce latency, the external synchronization signal shall be delayed internally to ensure that synchronization remains sample accurate.

2.3.3 Control gateway

In order to facilitate the monitoring and control of other subsystems, RSP acts as a gateway between the LCU and the RCU, SPU and TDS subsystems. The actual monitoring and control functions are implemented on the LCU. RSP merely forwards the low-level messages to the appropriate subsystem without knowledge about the contents of the messages.

2.3.4 Self test and diagnostics

The purpose of the self test and diagnostics functions is to detect hardware malfunctioning, both during power up and normal operation. Diagnosable items include:

- Local power supply voltages
- Temperature of local hardware devices
- Quality of internal communication links
- Quality of external communication links

In [RD.3] the diagnostic functions that are supported by RSP are specified in detail.

2.3.5 Remote update

In order to enable bug fixes and future enhancements, the firmware shall support remote upgrade. A fallback scenario to a factory image is provided in case the remote update fails. This function is specified in more detail in [RD.4].

2.4 Testing

The test strategy for the RSP firmware is defined in [RD.9]. The detailed RSP firmware tests are specified and listed in [RD.10].

3 Distributed data processing

3.1 Overview

A functional overview of the data processing path is shown in Figure 5. The algorithms used are described in more detail in [AD.4].

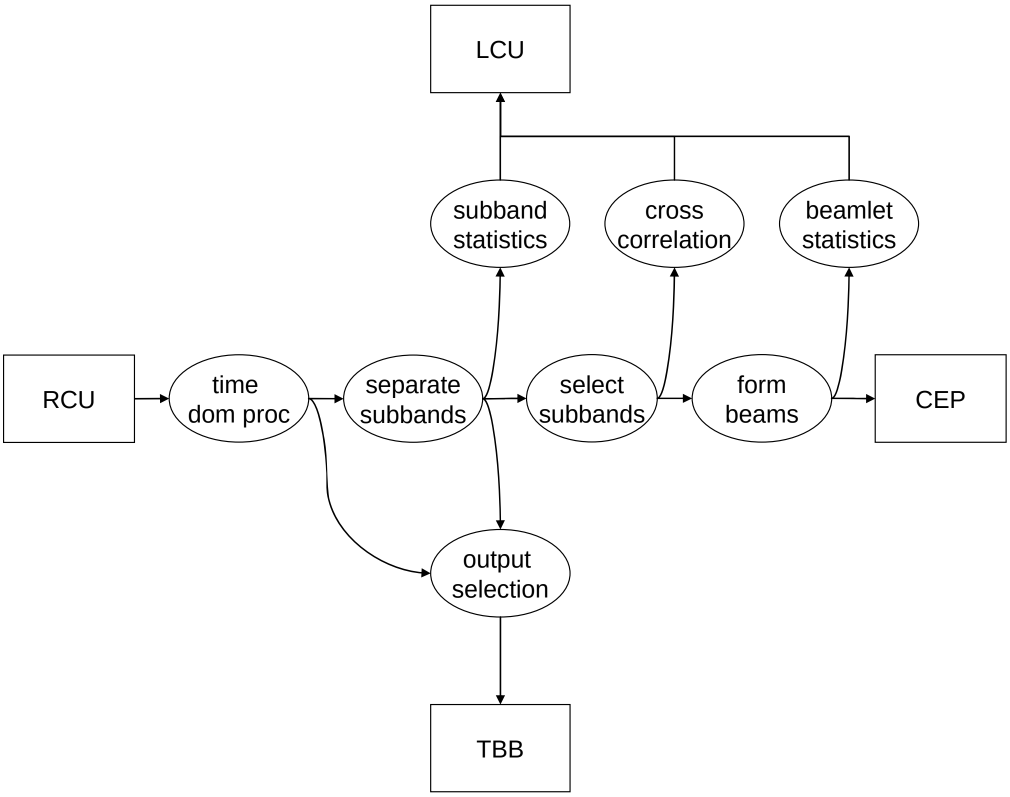

Figure 5: Functional overview of the data processing path

The incoming data from the RCU first goes through several time domain processing steps (i.e: sample based delay compensation, spectral inversion, removal of DC offset). The data is then converted to the frequency domain and separated into subbands. To enable spectral RFI monitoring, the power in each subband is computed. The 'select subbands' process performs the allocation of subbands to beamlets. The subband data is used both for cross correlation and to form beams. To enable monitoring of the beam quality, the power of each beamlet is computed and the beamlet data is sent to CEP. For the output to the TBB, either the time domain data or the frequency domain subband data can be selected. The LCU can read all statistics information, and controls the parameters settings of each process.

3.2 Quantization in the data processing

Any realistic digital processing system will use a finite number of bits to represent the samples. The RSP system shall be designed in such a way that the additional noise that is introduced by using a finite number of bits shall be less than the quantization noise of the A/D converter. Based on this specification we can derive the required number of bits in various parts of the system.

The input data that is receiver is 12 bits. Because the data is separated into 512 subbands, the quantization noise power will be distributed evenly among all subbands. Hence, the subbands should be represented by at least 12 + 0.5*log2(512) = 16.5 bits. Because the beam former adds the signals of all antennas, log2(100) = 7 bits are required to accommodate for the bit growth. Hence, the output of the station beam former is 24 bits. However, because the word size that is sent to CEP is limited to 16 bit samples (due to bandwidth and processing limitations), it shall be possible to configure for each beamlet to select which part of the 24 bit word is used.
The effects of re-quantization on the quality of the data output have been investigated extensively in [RD.8]. Based on the recommendations specified in this document, the following word sizes shall be using in practice:

- Antenna data shall be represented by real words of 12 bits.
- The filter coefficients shall be represented by real word of 16 bits.
- The FFT twiddle factors shall be represented by complex words of 2x16 bits.
- Subband data shall be represented by complex words of 2x18 bits.
- The beamlet coefficients shall be represented by words of 16 bits.
- Beamlet data shall be represented by complex words of 24 bits.

Simulations have shown that for these choices, the additional system noise that is added to the data due to re-quantization is less than the quantization noise of the A/D converter.

3.3 Mapping of functions onto the hardware platform

In order to minimize the required communication bandwidth, an architecture has been chosen for the digital processing functionality that minimizes the required communication bandwidth (see [AD.1]). The building blocks for the digital processing are RSP boards that are connected in a ring. Almost all data processing functions are performed on the Antenna Processor (AP), except for the cross correlation and beamlet statistics which are performed on the Board Processor (BP).

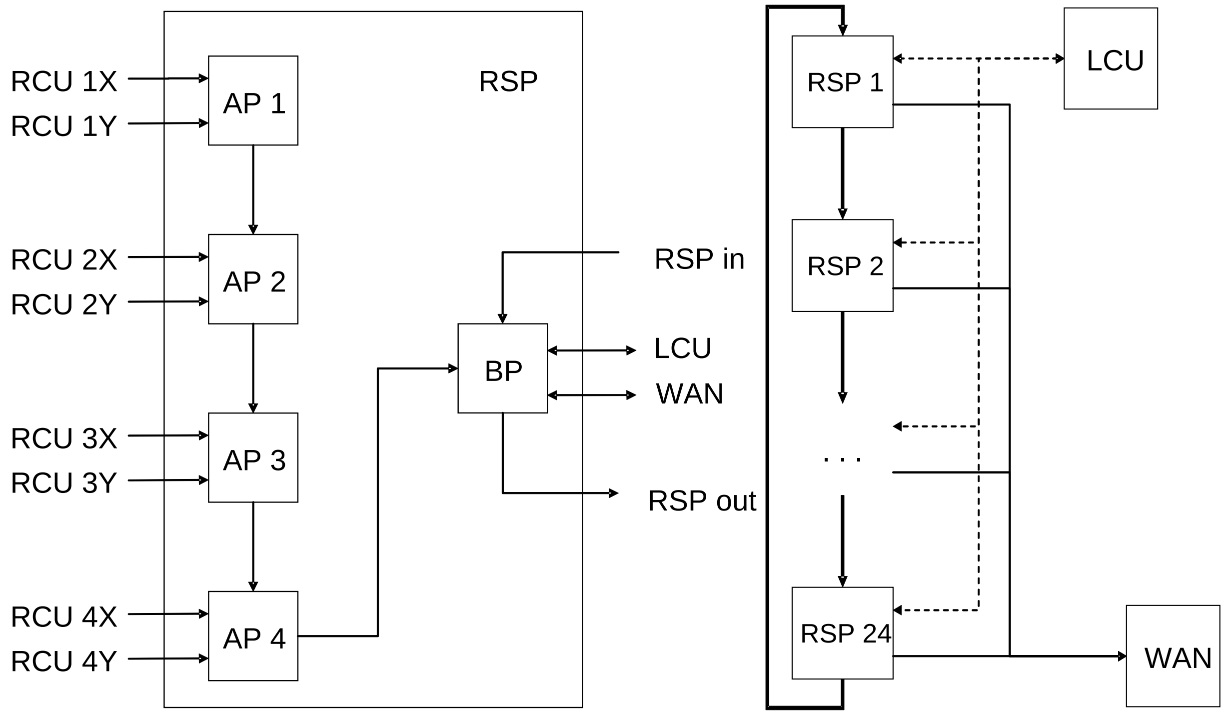

Figure 6: Overview of the remote station digital processing architecture. On the left the RSP board, on the right the remote station topology.

Not required, but if feasible it should be possible to change the direction of the on board data ring between the BP and the AP. Not required, but if feasible it should be possible to change the direction of the board-to-board data ring.

3.3.1 Distribution of the station beam forming function

A consequence of the architecture is that the station beam forming function is distributed over all processing units. This can be done by splitting it into two parts, the ‘beamlet transformation’ and the ‘beamlet addition’. Figure 7 shows the adder tree structure that is used for the beamlet addition.

3.3.2 Distribution of the station cross correlation

The cross correlation function is distributed in a similar way. On each RSP board, the local crosslets obtained from the APs are cross correlated on the BP with the remote crosslets, and inserted into the data stream. For each crosslet, a separate slot is allocated in the data frames that exchanged between the RSP boards.

3.3.3 Distribution of the station output

The output to CEP shall be distributed over 4 output channels. For each output, a separate ‘lane’ is used in the board-to-board data link (see Figure 9). Each lane has a different start and end point. In case of a failure on one of the boards or one of the links between the boards, antenna data will be lost. Depending on the relative location of the failure in the lane, the data loss for that lane will be between 0 and 100%. In order to limit the impact of a failure, the end points of the lanes can be reconfigured in such a way that the loss is minimized, i.e. by having the end points as close as possible to the failure point.

RSP shall support detection of link and board failures, but lane reconfiguration itself will be controlled by the LCU. Note that all RSP boards have to be connected to the WAN for the fault impact minimization to be effective.

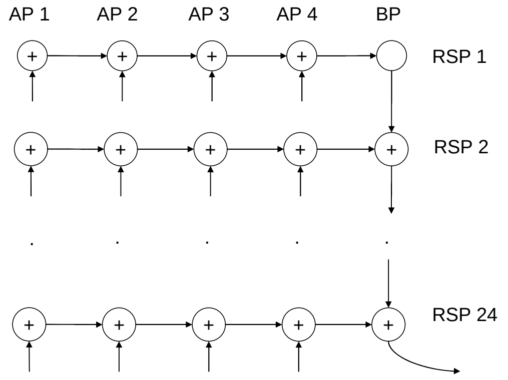

Figure 7: Distributed station beam forming

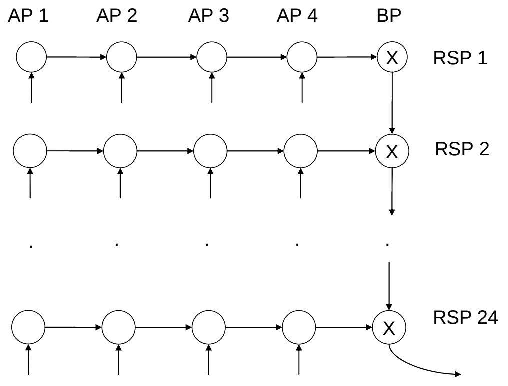

Figure 8: Distributed correlation

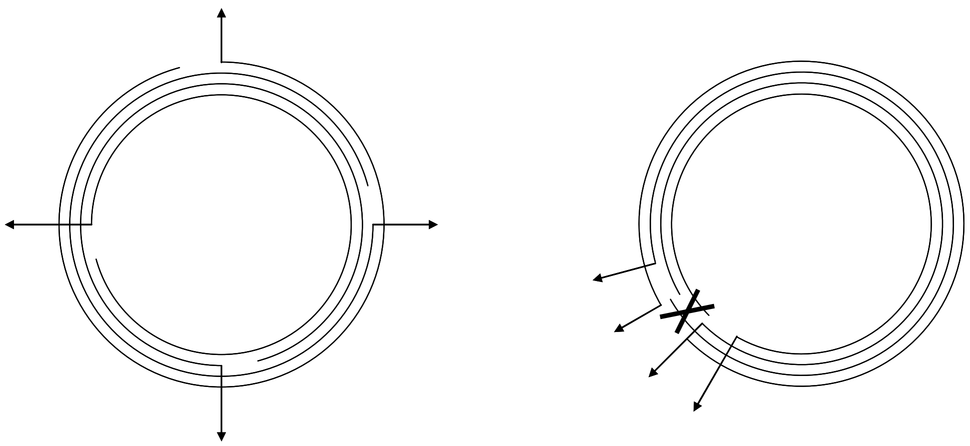

Figure 9: Distributed output using 4 lanes.
Left picture shows normal operation,
right picture shows a possible lane reconfiguration in case of failure.