Detailed Design of the Arts FPGA Beamformer

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Document history:

Revision	Date	Author	Modification / Change
0.1	2015-05-13	E. Kooistra	First draft that describes the CB input.

Table of contents:

References:

[1] "Arts Requirements Specifiction", ASTRON-RS-020, J. van Leeuwen
[2] "Apertif System Requirement Specification", ASTRON-RS-006, Rev C, W.A. van Capellen
[3] "Detailed Design of the Digital Beamformer System for Apertif", ASTRON-RP-413, G. Schoonderbeek, A. Gunst, E. Kooistra
[4] "Apertif Beamformer Firmware Description", ASTRON-RP-1377, D. vd Schuur
[5] "Detailed Design of the Correlator System for Apertif", ASTRON-RP-1400, G. Schoonderbeek, A. Gunst, E. Kooistra, HJ Pepping
[6] "Representing Streaming Data", ASTRON-RP-1486, E. Kooistra
[7] "Apertif Beamformer Output Interface Specification", ASTRON-SP-061, E. Kooistra
[8] "Understanding Digital Signal Processing", 3rd edition, R. Lyons
[9] "Apertif Filterbank Firmware Specification Part 2", ASTRON-SP-054, E. Kooistra
[10] "Selection and Reorder modules", ASTRON-RP-1399, H.J. Pepping
[11] "Uthernet interface specification", ASTRON-SP-041, E. Kooistra
[12] "Data path packet interface specification", ASTRON-SP-042, E. Kooistra

Terminology:

ADC	Analogue to Digital Conversion
AGC	Automatic Gain Control
Apertif	APERture Tile In Focus
Arts	Apertif Radio Transient System
beam	Group of beamlets that point in the same direction
beamlet	Beam formed subband, a small beam spanning one subband
BF	BeamFormer
BN	Back Node FPGA on UniBoard
bps	Bits per second
BSN	Block Sequence Number (timestamp)
BW	BandWidth
CB	Compound Beam, formed at dish level over the FPA
channel	Unit frequency band within a beam
CPU	Central Processing Unit
CW	Carrier Wave (single frequency signal)
DP	Data Path (streaming interface)
eop	End of Packet (or frame, or block)
ephemeris	Pulsar data format file with the parameters used in the timing model
FFT	Fast Fourier Transform
FN	Front Node FPGA on UniBoard
FoV	Field of View
FPA	Focal Plane Array (= PAF)
FPGA	Field Programmable Gate Array
FR	Functional Requirement
FRB	Fast Radio Burst
GbE	Gigabit Ethernet
GPU	Graphics Processing Unit
HDL	Hardware Description Language
IAB	Incoherent array beam, formed by incoherently combining dishes
Im	Imaginary
IO	Input Output
LEAP	Large European Array for Pulsars
MAC	Multiply and Accumulate, Medium Access, Monitoring and Control
MM	Memory Mapped (control interface)
node	Processing node (PN), typically 1 FPGA chip
Nof	Number of
OEB	Optical-Electrical Board (provides UniBoard BN with same optical IO as the FN)
PFB	Poly phase Filter Bank
power beam	Full Stokes power values: I, Q, U, V
PAF	Phased Array Feed (= FPA, better use term FPA)
PL	Pipeline processing
PN	Processing Node (BN or FN)
PPS	Pulse Per Second
Re	Real
RF	Radio Frequency
SC	Science Case
SNR	Signal to Noise Ratio
sop	Start of Packet (or frame, or block)
SP	Signal Path, 1 CB consists of N_{pol} = 2 SP, 1 SP per Apertif BF subrack
SR	Science Requirement
ST	Streaming, statistics
sps	Samples per second
subband	Frequency band, unit output of the filterbank

TAB	Tied array beam, formed by coherently combining dishes
T_{ant}	Transpose to group data from all S = 64 (≥ N_{ant}) antenna elements in the FPA
T_{dish}	Transpose to group data from all N_{dish} = 12 dishes
T_{pol}	Transpose to group data from both N_{pol} = 2 polarizations
T_{sp}	Transpose to group data from all N_{sp} = N_{pol} * N_{dish} signal paths, so combines T_{dish} and T_{pol}
T_{band}	Transpose to group data from all N_{band} = 16 bands
$T_{integration}$	Transpose to group data from an integration interval
T_{FoV}	Transpose to group data from all N_{CB} = 37 beams for the full FoV
ToA	Time of Arrival
TT	Terrestrial Time
VDIF	VLBI Data Interchange Format
VLBI	Very Large Baseline Interferometry
voltage beam	Dual polarization sample values with phase information: X_{re}, X_{im}, Y_{re}, Y_{im}
WSRT	Westerbork Synthesis Radio Telescope
X	Correlator

Definitions:

$N_{complex}$	2	Two part of a complex number, the real and imaginary part
N_{pol}	2	Number of polarizations, X and Y
N_{Stokes}	4	Number of power values in the Stokes vector [I, Q, U, V]
N_{dish}	12	Number of WSRT dishes in Apertif
N_{sp}	24	Number of signal paths = N_{dish} * N_{pol}
N	1024 or 800	FFT size of the FFT in the Apertif BF subband polyphase filter
P	4	Wideband rate factor of sample clock rate divided by digital processing clock rate
N_{clk}	256 or 200	= N/P, number of DP clock cycles per subband period
N_{sub}	512	= N/2, number of subbands that covers RF_{BW}=400MHz
N_{sel}	384	Number of selected subbands to cover CB_{BW}=300 MHz
N_{band}	16	= nof_fn_bf, Number of bands in the Apertif BF to process the full CB_{BW}
N_{FN}	24	Number of subband per FN in the Apertif BF (= N_{sel}/N_{band})
N_{CB}	37	Number of compound beams
K	40	Average number of beamlets per subband (≥ N_{CB})
P_{BF}	4	Number of parallel BF units per FN
N_{blk}		≤ N_{clk}, number of valid DP clock cycles per subband period
$N_{beamlet}$		Number of compound beamlet slots per FN output, maximum P_{BF} * N_{clk} = 1024, actual P_{BF} * N_{blk} = 960, required N_{CB} * N_{FN} = 888
$N_{interleave}$	2	= nof_un/P_{BF}, additional beamlet output interleave factor
$P_{interleave}$	2	Number of interleaved streams that are regarded in parallel at rate 1/$P_{interleave}$
N_{gr}	12	Number of grating lobe patterns TABs to cover the full CB (SR-0.41)
N_{VLBI}	12	Number of TABs in the central CB for VLBI, choose = N_{gr} (SR-0.23)
N_{IAB}	37	= N_{CB}, number of IABs
N_{TAB}	444	Number of TABs
N_{PN}	384	= N_{sp} * N_{band}, total number of parallel processing nodes in the Apertif BF
N_{link}	384	= N_{PN}, number of physical 10G output links of the Apertif BF, so 1 link per PN
N_{ant}	61	Number of antennas in the frontend FPA of the Apertif BF
S	64	Number of ADC signal paths in the frontend FPA of the Apertif BF (≥ N_{ant})
S_{BN}	4	Number of ADC signal paths per BN in the frontend FPA of the Apertif BF
f_{clk}	200M	Data processing clock rate in the FPGA
f_s	800 MHz	Digitizer sample frequency of the ADC at the Apertif BF frontend
T_s	1.25 ns	= 1/ f_s, digitizer sample period
f_0		Lower edge frequency of a subband, beamlet or channel
RF_{BW}	400 MHz	= f_s/2, sampled RF bandwidth
CB_{BW}	300 MHz	Full bandwidth of the CB and also of the TAB and IAB (SR-0.2)
B_{sub}	781250 Hz	Subband bandwidth in Apertif BF, = beamlet bandwidth
N_{chan_x}	64	Number of channels per beamlet in the Apertif X

N_{chan}	4	Number of channels per beamlet, for SC3 and SC4
B_{chan}		= B_{sub}/N_{chan}, channel bandwidth within a beamlet, for SC3 and SC4
N_{int_x}	800000	Number of channel power values that are integrated in the Apertif X
N_{int}	≈ 10	Number of Stokes channel power values that are integrated in Arts
T_{Stokes}	≈ 50 µs	Minimum required sample period for the Stokes power values
f_{Stokes}	≈ 20 kHz	= $1/T_{Stokes}$, minimum required sample frequency for the Stokes power values
nof_uni	4	Number of UniBoards per polarization and dish in the Apertif BF
nof_bn	4	Number of back node FPGAs (BN) per UniBoard
nof_fn	4	Number of front node FPGAs (FN) per UniBoard
nof_un	8	= nof_fn + nof_bn, number of processing node FPGAs per UniBoard
nof_10g	3	Number of 10G links per FPGA node on UniBoard
nof_pn		Number of processing nodes (BN or FN)
nof_bn_fb	16	= nof_uni*nof_bn, number of subband filterbank BN per SP in the Apertif BF
nof_fn_bf	16	= nof_uni*nof_fn, number of beamformer FN per SP in the Apertif BF
byte_w	8	Number of bits in a byte or an octet
word_sz	4	Number of bytes per 32 bit long word
longword_sz	8	Number of bytes per 64 bit long word
$W_{beamlet}$	6	Word width in number of bits of a beamlet voltage sample
W_{chan}		Word width in number of bits of a channel voltage sample
W_{tab}	4	Word width in number of bits of a TAB voltage sample
W_{power}	4	Word width in number of bits of a IAB or TAB power sample

1 Introduction

1.1 Scope

Arts [1] implements the tied array and VLBI functionality of Apertif [2]. Figure 1 shows the place of Arts within Apertif. Both the Apertif correlator (X) [5] and Arts use the beam data from the Apertif beamformer (BF) [3].

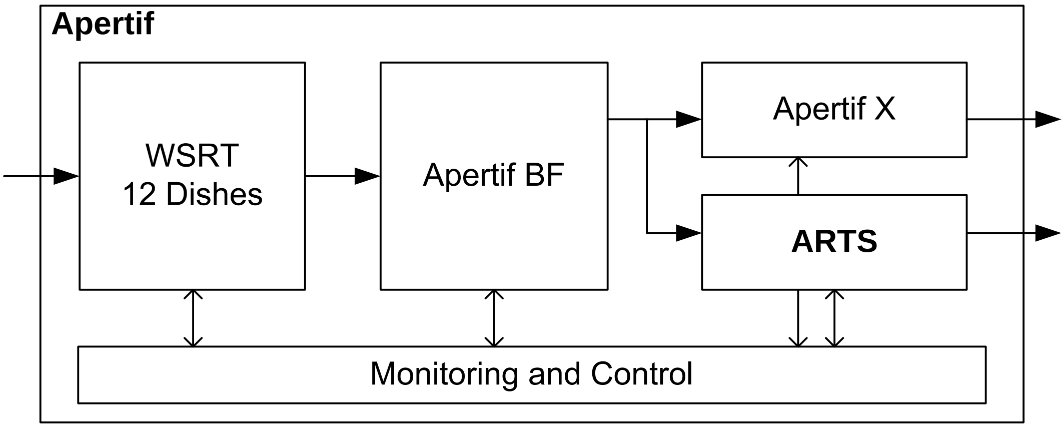

Figure 1: Top level overview of Apertif with Arts included

Within Arts the processing is consists of a FPGA beamformer and a GPU pipeline, as shown in Figure 2. Arts has four science cases (SC) and for all four SC the FPGA beamformer will be implemented on Uniboards.

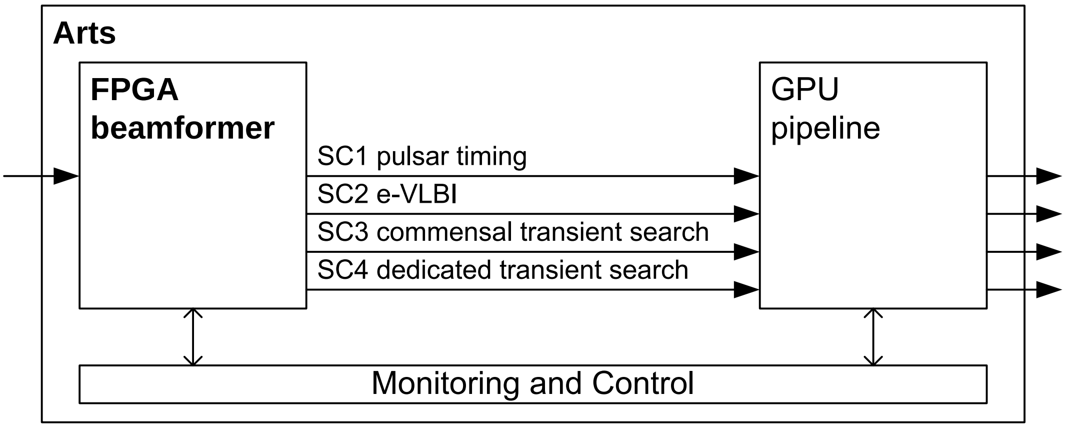

Figure 2: Arts FPGA beamformer and GPU pipeline

This document specifies the detailed design for the Arts FPGA beamformer (BF) on UniBoard FPGAs. At the input interface the Arts BF receives N_{CB}=37 compound beams from N_{dish}=12 dishes from the Apertif BF. At the output interface the Arts BF outputs compound beams (CB) for SC2, tied array beams (TAB) for SC1, 2 and 4 or incoherent array beams (IAB) for SC3 to a GPU cluster for further processing.

Note the difference between the Apertif BF and the Arts BF. The Apertif BF forms the compound beams over the focal plane array of each dish. These compound beams are input to Aperitif X and to Arts. The Arts BF uses the compound beams to form IAB or TAB over the array of dishes.

1.2 Specification

This detailed design document is the L3 specification of the FPGA beamformer because it specifies how the FPGA beamformer should be implemented on Uniboards to fulfill all L0 science, L1 system and L2 subsystem requirements that are specified in [1]. This document only specifies the FPGA firmware design and the required FPGA interconnect and IO architecture. The UniBoard hardware and the subrack hardware are assumed to be available.

2 System overview

2.1 Apertif BF subsystem

The Apertif BF separates the digitized data from the FPA into subbands by means of a filterbank and then it forms beamlets for these subbands. The beamforming (BF) for one single polarization of the FPA cannot be done on a single node for the full bandwidth, so therefore the subband load has to be distributed across N_{band} = nof_fn_bf = 16 processing nodes. The beamlet for one subband requires the input from all FPA elements, so therefore there needs to be a transpose T_{ant} that groups the subbands from all S = 64 antennes. A CB is formed by a group of N_{sel}= 384 beamlets all with the same direction that span the CB_{BW} = 300 MHz. Figure 3 shows the filterbank F_{sub}, the transpose T_{ant} and the beamformer (BF) that is distributed over N_{band} nodes. The $T_{integration}$ transpose is used for the Apertif X, for Arts it needs to be bypassed. The MAC takes care of the proper operation, the subband selection and the BF weights.

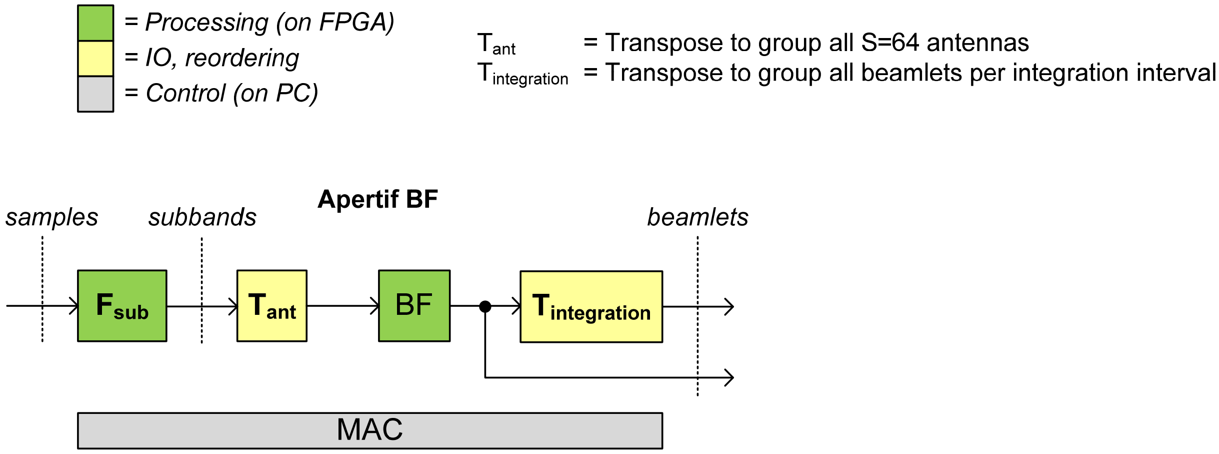

Figure 3: The Apertif BF subsystem

2.2 Apertif X subsystem and Arts subsystem

In [1] various options for the Arts subsystem were investigated. Figure 4 shows the selected option for the Arts subsystem and how it relates to the Apertif X subsystem. The same T_{dish} and T_{pol} transpose that are needed for Apertif X can also be used for Arts.

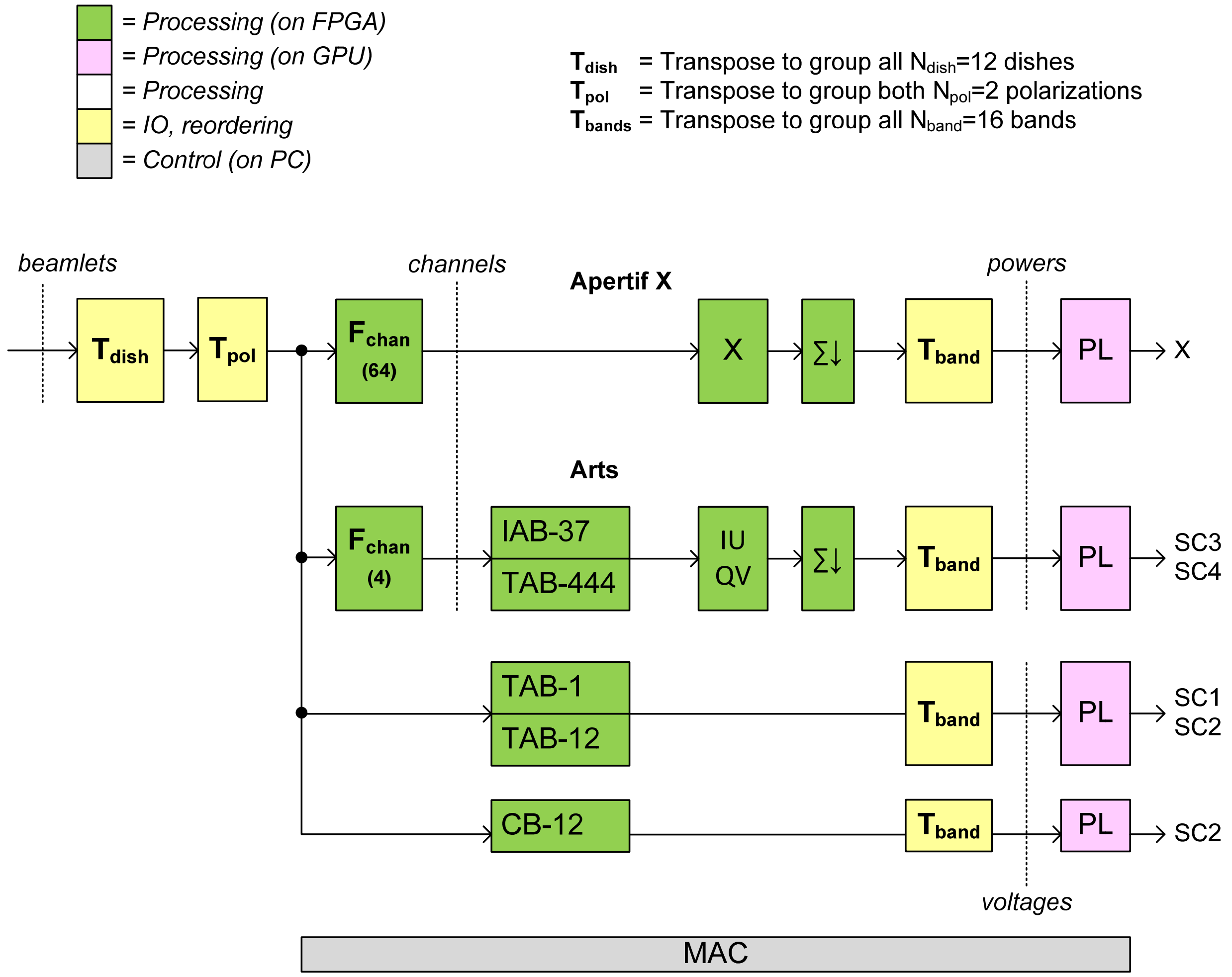

Figure 4: The Apertif X subsystem and the Arts subsystem

3 Hardware architecture

3.1 Apertif BF using Uniboard

The Apertif BF outputs N_{CB}=37 compound beams with CB_{BW}=300 MHz. The Apertif BF beam forms the FPA input per polarization and per dish. The single dish, single polarization output of the Apertif BF is called a signal path (SP) and to beam form 1 signal path requires a subrack with nof_uni=4 UniBoards. To be able to distribute the processing over nof_fn_bf=16 front nodes (FN) on nof_uni=4 UniBoards the Apertif BF is separated into N_{band}= nof_fn_bf =16 frequency bands. Figure 5 shows the Apertif BF subrack with 4 UniBoards. Each FN in the subrack uses one 10GbE port to output its frequency part of the signal path.

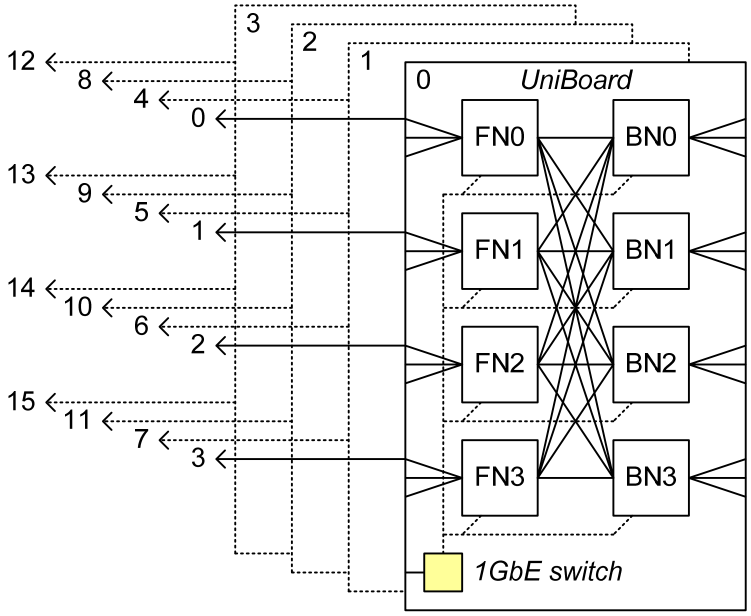

Figure 5: One Apertif BF subrack per signal path with nof_uni=4 UniBoards and N_{band}=16 FN

3.2 Signal path transpose to Arts

In total the Apertif BF has N_{sp} = N_{pol} * N_{dish} = 24 signal paths so also 24 subracks, 96 UniBoards and N_{PN}=N_{sp}*N_{band} = 384 processing (front) nodes. Hence the total Apertif BF output is carried via N_{link}=N_{PN}=384 10GbE links as shown in Figure 6. For both the Apertif X and for Arts the N_{sp}=24 signal paths from the Apertif BF need to be transposed to gather them together. This transpose T_{sp} can be implemented by interconnecting the Apertif BF to N_{band}=16 Uniboards as shown in Figure 6. Each of the N_{band}=16 UniBoards in Figure 6 processes 1/N_{band} part of the CB_{BW} band for all N_{sp}=24 signal paths.

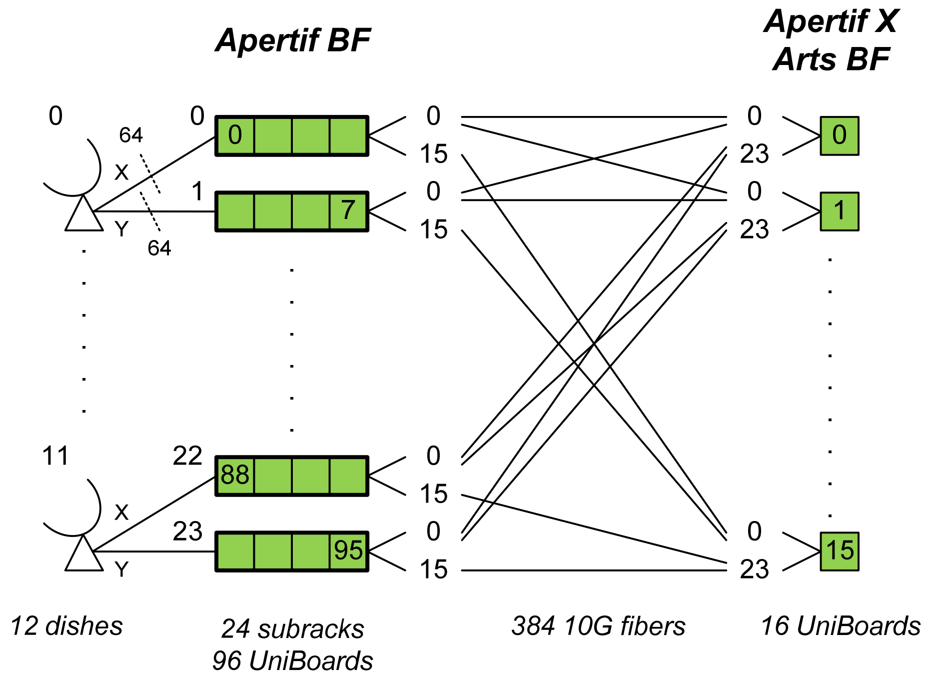

Figure 6: Apertif BF transpose interconnect to Apertif X and Arts

3.3 Arts using UniBoard

Figure 7 shows the UniBoard with the Optical-Electrical Board (OEB). The OEB is needed to be able to use fiber optics IO for the BN. For the Arts application (and also for the Apertif X application) the distinction between FN and BN is not needed, because all nof_un = nof_fn + nof_bn = 8 FPGA have the same function. Therefore the FPGAs on UniBoard are also referred to as processing nodes (PN). Each PN has nof_10G = 3 10G links so in total the UniBoard has nof_un * nof_10G = 24 10G links. This is just enough IO to accept the input from N_{sp}=24 links.

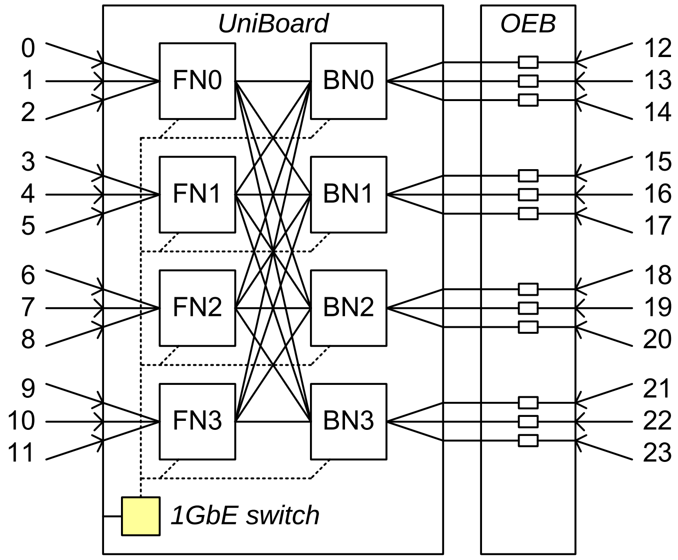

Figure 7: One UniBoard to process 1/N_{band} part of the CB_{BW} for N_{sp}=24 signal paths

On UniBoard the N_{sp}=24 inputs need to be distributed further via the on board mesh interconnect to gather them together at each PN. Therefore the input needs to be divided into 1/nof_un parts to evenly distribute the processing load over the PN.

4 Interfaces

4.1 Streaming data

The array notation for streaming data is explained in [6].

4.1.1 CB signal path input

4.1.1.1 Entire system

The compound beam data output interface of the Apertif BF is defined by [7]:

Equation 1: $$(\boldsymbol{cint6})\boldsymbol{CB}_{\boldsymbol{dish},\ \boldsymbol{pol},\ \boldsymbol{band}}[\boldsymbol{t}][\boldsymbol{b}]$$

The wiring of the N_{link}=384 10GbE links in Figure 6 implements the first part of the T_{dish} and T_{pol} transpose to group the SP data from all N_{sp}=24 signal paths per band at a single UniBoard. The T_{dish} and T_{pol} transposed beam data input for Arts BF (and also for Apertif X) is defined by (note the swapped band and dish indices):

Equation 2: $$(\boldsymbol{cint6})\boldsymbol{CB}_{\boldsymbol{band},\ \boldsymbol{pol},\ \boldsymbol{dish}}[\boldsymbol{t}][\boldsymbol{b}]$$

The subscript indices indicate parallel links and the array index contains serial data on the link. The subscript *band* has range 0:N_{band}-1, subscript *pol* has range 0:N_{pol}-1, subscript *dish* has range 0:N_{dish}-1. In total there are N_{band} * N_{pol} * N_{dish} = 16 * 2 * 12 = N_{link} = 384 parallel links. The array index *t* increments at the rate of B_{sub}. The array index *b* has range 0:$N_{beamlet}$-1 where $N_{beamlet}$ is the number of compound beamlet slots per FN output of the Apertif BF. Required $N_{beamlet} \geq N_{CB}$*N_{FN} = 37 * 24 = 888, note that N_{FN} = N_{sel} / N_{band}. The actual $N_{beamlet}$ = K*N_{FN} = 40 * 24 = 960. The order of beamlet directions and beamlet frequencies can be mapped to the beamlet slots in almost any order by the reorder function in the Apertif BF.

The order of the subscript indices indicates that band 0 maps on UniBoard 0 and band 15 maps on UniBoard 15. The pol index before the dish index implies that the X-pol inputs are connected via stream [0:11] to FN0:3 and the Y-pol inputs are connected via stream [12:23] to BN0:3 as shown in Figure 7. Based on this the *pol* and *dish* indices can be mapped to *port* and *pn* indices and to index *sp* = 0:N_{sp}-1 = 0:23 according to:

Equation 3: $$\boldsymbol{sp} = \boldsymbol{dish} + \boldsymbol{pol} * \boldsymbol{N}_{\boldsymbol{dish}} = \boldsymbol{port} + \boldsymbol{dish} * \boldsymbol{nof\_10G}$$

Equation 4: $$\begin{aligned}\boldsymbol{pol} &= \boldsymbol{sp}\ \boldsymbol{MOD}\ \boldsymbol{N}_{\boldsymbol{pol}}\\ \boldsymbol{dish} &= \boldsymbol{sp}\ \boldsymbol{DIV}\ \boldsymbol{N}_{\boldsymbol{pol}}\end{aligned}$$

Equation 5: $$\begin{aligned}\boldsymbol{port} &= \boldsymbol{sp}\ \boldsymbol{MOD}\ \boldsymbol{nof\_10G}\\ \boldsymbol{pn} &= \boldsymbol{sp}\ \boldsymbol{DIV}\ \boldsymbol{nof\_10G}\end{aligned}$$

With Equation 3 the Equation 2 can be rewritten as:

Equation 6: $$(\boldsymbol{cint6})\boldsymbol{CB}_{\boldsymbol{band},\ \boldsymbol{pn},\ \boldsymbol{port}}[\boldsymbol{t}][\boldsymbol{b}]$$

4.1.1.2 Per UniBoard

One UniBoard processes one band of all N_{sp}=24 SP. Call this signal CB_band, so CB_band = CB_{band} where *band* is mapped to this UniBoard. For one UniBoard equation Equation 6 then reduces to:

Equation 7: $(cint6)CB\_band_{pn,\ port}[t][b]$

Internally the Apertif FN beamformer contains P_{BF}=4 parallel BF units that each process N_{clk}=256 beamlets to achieve $N_{beamlet}$= P_{BF} * N_{clk}=1024 in total. From these N_{clk} beamlets only N_{blk}=240 are actually output [7]. With subscript *u* = 0:P_{BF}-1 = 0:3 to indicate the parallel BF units and index *bu* = 0:N_{blk}-1 = 0:239 to count the number of valid beamlet slots per BF unit, then the relation with the absolute beamlet index *b* is given by:

Equation 8: $b = u * N_{clk} + bu$

With Equation 8 the Equation 7 can be rewritten as:

Equation 9: $(cint6)CB\_band_{pn,\ port,\ u}[t][bu]$

4.1.1.3 Distribution on the UniBoard mesh

Next part to complete the T_{dish} and T_{pol} transpose is to bring all SP to one processing node (PN) on UniBoard. Therefore the beamlets that are received at each PN need to be split into nof_un=8 parts, whereby one part is kept at this PN and the other nof_un-1 = 7 parts are passed on via the UniBoard mesh to the other 7 PN on the UniBoard. Choose to distribute the beamlets over the nof_un=8 in the order in which they arrive at the PN. The index *u* already provides range P_{BF}=4 beamlets, therefore define an additional interleave subblock size of $N_{interleave}$ = nof_un/P_{BF} = 2 beamlets to be able to distribute the beamlets in order over the nof_un=8 PN. Equation 9 can then be rewritten as:

Equation 10: $(cint6)CB\_band_{pn,\ port,\ u}[t][bu\_i][bi]$

Whereby the relation between index *bu* and index *bi* = 0:$N_{interleave}$-1 =0:1 and *bu_i* = 0:N_{blk}/$N_{interleave}$-1 = 0:119 is given by:

Equation 11: $bu = bu\_i + bi * N_{interleave}$

Define index *dest* = 0:nof_un-1 = 0:7 for the destination PN as:

Equation 12: $dest = u + bi * N_{interleave}$

With Equation 12 the Equation 10 can be rewritten as:

Equation 13: $(cint6)CB\_band_{pn,\ port,\ dest}[t][bu\_i] \quad @\ 1/P_{interleave}$

Whereby the $N_{interleave}$ = 2 beamlets in series are regarded as $P_{interleave}$ = $N_{interleave}$ = 2 parallel streams that run at 1/$P_{interleave}$ rate of f_{clk}.

Equation 14: $d = u * N_{clk} + bu$

Together the indices *port* and *dest* cover the entire range of SP, because $N_{sp}=N_{link}$*nof_un=3*8=24. The order of the indices *port* and *dest* can be swapped at no cost, because all streams are available in parallel within the PN FPGA. It is convenient to swap *port* and *dest*, because then the N_{sp}=24 streams are again in incrementing order. Therefore rewrite Equation 13 as:

Equation 15: $(\boldsymbol{cint6})\boldsymbol{CB\_band}_{\boldsymbol{pn},\ \boldsymbol{dest},\ \boldsymbol{port}}[\boldsymbol{t}][\boldsymbol{bu\_i}] \quad @\ \mathbf{1}/\boldsymbol{P}_{\boldsymbol{interleave}}$

The beamlets stream for which index *pn* = *dest* remains on this PN and the beamlet streams for which *pn* != *dest* are received from the corresponding other PN via the UniBoard mesh. This transport operation across the UniBoard mesh implements the last part of the T_{dish} and T_{pol} transpose. Starting with Equation 10 this swaps the *dest* and *pn* indices and results in:

Equation 16: $(\boldsymbol{cint6})\boldsymbol{CB\_band}_{\boldsymbol{dest},\ \boldsymbol{pn},\ \boldsymbol{port}}[\boldsymbol{t}][\boldsymbol{bu\_i}] \quad @\ \mathbf{1}/\boldsymbol{P}_{\boldsymbol{interleave}}$

With Equation 3 the Equation 16 can be expressed in terms of the SP index *sp* = 0:N_{sp}-1:

Equation 17: $(\boldsymbol{cint6})\boldsymbol{CB\_band}_{\boldsymbol{dest},\ \boldsymbol{sp}}[\boldsymbol{t}][\boldsymbol{bu\_i}] \quad @\ \mathbf{1}/\boldsymbol{P}_{\boldsymbol{interleave}}$

4.1.1.4 Per PN

One processing node (PN) on UniBoard processes 1/nof_un = 1/8 part of the beamlets of one band of all N_{sp}=24 SP. Call this signal cb_band, so cb_band = CB_band_{dest} where *dest* is this PN. For one PN Equation 17 then reduces to:

Equation 18: $(\boldsymbol{cint6})\boldsymbol{cb\_band}_{\boldsymbol{sp}}[\boldsymbol{t}][\boldsymbol{bu\_i}] \quad @\ \mathbf{1}/\boldsymbol{P}_{\boldsymbol{interleave}}$

4.1.2 BF component input and output

The BF component that is used in the FN of the Apertif BF is a voltage beamformer and can therefore also be reused to beamform TABs.

4.1.3 SC1 TAB1 output

4.1.4 SC2 CB12 output

4.1.5 SC2 TAB12 output

4.1.6 SC3 IAB37 output

4.1.7 SC4 TAB444 output

4.2 Memory-mapped control

5 Processing

6 Storage