



Memo 110

Cost and power usage evaluations for the various processing architectures:

A Hardware and Operational Cost Comparison of Two Architectures for Large Scale Focal Plane Array Beamforming and Correlation.

A. W. Gunst

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1 Scope

This document is an architectural study for one of the pathfinders for the SKA: Apertif, a phased focal plane array system for the WSRT. The aim is to compare two different DSP platforms which are developed and will be developed for SKA pathfinders, Roach and Quinten. Both types of platforms differ significantly in their design philosophy. This document discusses consequences of the different design approaches on development time, hardware costs, and power consumption.

2 Introduction

In this document the Astron Quinten system [7] and the Roach technology developed in the Casper community [1] are compared for the Apertif application. For this application two main types of processing are considered: beam forming and correlation. Since the Quinten design is not finished yet, the comparison is based on the current ideas. Furthermore, only the digital boards and part of the infrastructure (switches and interconnect) is costed. So, the cabinets, power supply and clock distribution hardware is not considered in this comparison.

The first platform under consideration is the recently produced Casper hardware [4]: the Roach board. The current trend in the Casper community is to build boards with one FPGA mounted on the board. This FPGA is typically the largest one available at the time of development. A system can be build from these boards by connecting the boards to each other via commercial off the shelf switches. The philosophy of the Casper group is that the switch companies solve the interconnect problem, i.e. the “transpose” or corner turner operation required in the signal processing chain for astronomical applications. This operation is required because the correlators currently under development are FX correlators [1]. Furthermore, the design flow used for the Casper hardware is user friendly and even non-engineers seem to be able to build a system with the hardware. A consequence of this philosophy is that users are able to build systems with the Casper hardware rapidly.

The second platform under consideration is the Quinten DSP hardware to be developed at ASTRON in collaboration with JIVE and other European partners. The Quinten hardware will be based on UniBoard, a DSP board to be developed in the European RadioNet UniBoard project. This system can be used for a variety of applications. This initiative was also taken to be a stepping stone towards the digital hardware necessary for large instruments like pathfinders for SKA and also a new correlator for the EVN. Hence, the Quinten system aims at the high-end applications. As a consequence, cost, power consumption and physical dimensions become even more important parameters. Therefore a philosophy of Quinten is to maximize the efficiency of processing and I/O in terms of power, cost and physical dimensions. Obviously this implies to integrate functionality as much as possible on a chip. If the complexity is too large for a single chip then the next design rule is to keep the functionality as much as possible onto one single circuit board. This requirement implies the use of multiple chips on a board. For even larger systems, as targeted with Quinten, the functionality is kept in a subrack and if that is too small, the processing is distributed over (multiple) cabinets. A crucial assumption is that also the interconnections are kept as local as possible (at chip, board, subrack and cabinet level). For most real-time radio astronomical applications the route of the signals is known beforehand and hence a fixed board or subrack interconnect design gives sufficient flexibility.

A consequence of the Quinten architectural philosophy is that the development time is longer as compared to the architecture approach of Casper sketched above. However, for large scale beamforming and correlation, the hardware costs when using the Quinten approach are much lower than when using the Casper-Roach approach. Also, the operational cost (power consumption) and physical dimensions of a Quinten based architecture are much lower, as will be clarified in this memo.

3 Apertif Application

In the Apertif project a focal plane array is developed for the Westerbork Synthesis Radio Telescope. Each focal plane array consists of 56 antenna elements, each with two polarizations. The number of beams to be generated for each focal plane array is 25. Furthermore, the digitization will be done prior to beamforming. The focal plane arrays will be installed on 12 telescopes. At the central site all twelve telescopes and dual polarized signals have to be correlated with each other for all 25 beams. Since all beams can be treated independent of each other, the correlator grows linearly by the number of beams. Furthermore, for the correlator uses an FX architecture. In this architecture the correlation processing can be distributed efficiently per frequency (sub) band. Both the Quinten and Roach technology make use of this type of distribution.

The analog input bandwidth of each signal path is set to 400 MHz and coded in 8 bit. This results per signal path in a data rate of 6.4 Gbps. The total input data rate is this number multiplied with the number of antennas in the FPA (56), the number of polarizations (2), and the number of telescopes (12).

Each beam is assumed to have a bandwidth of 300 MHz and coded in 16 bit (8 bit complex). Hence, 25 single polarized beams of a telescope fit exactly in 12 10 Gbps interfaces as is used for both technologies. To calculate the total data rate this number should be multiplied by the number of telescopes (12) and the number of polarizations (2).

4 Assumptions

To make a fair comparison between the Roach and Quinten technology, the following assumptions are made:

- The number of FPGAs for both technologies is the same.
- The type of FPGA is the same for both technologies (although for Quinten we anticipate another FPGA, in the analysis we used the same type).
- The cost assumes market prices for the FPGAs.
- The interfaces from the antenna elements to the digital hardware is assumed to be differential (compatible for both Roach and Quinten), while all the other interfaces are assumed to be 10 Gb links.

5 Implementation with Roach Technology

The Roach board consists of one FPGA of Xilinx, type XC5VSX95T. Furthermore, it can interface in total with 4 serial links of 10 Gbps and 2 times 40 differential pairs to a receiver interface. The cost breakdown of a Roach board is listed in Table 1.

Item	Cost (\$)
Board	2500
FPGA	2000
Rest	500
Total board	5000

Table 1 Roach board cost breakdown [1]

The board cost includes not only the printed circuit board as such, but also all non-FPGA components such as connectors, power distribution components, memory etcetera. The Roach boards can be connected to each other via switches to form a system. For the switch the costs are assumed 600\$ per switch port. Furthermore, a switch of maximal 16 CX4 ports of 10 Gbps is assumed since those types are used for the current Casper applications. The maximal number of ports is important to note, because the required number of switches grows if more than 16, 10 Gbps ports have to be used. This is because the data have to be transported from switch to switch also using ports. The switch under consideration has 4 extra ports for interconnect in between switches via fibre. Also these extra ports are accounted for in the comparison. Finally the 10 GbE cables are estimated for 65\$ each (4m length). Since the cost of the

cables is not significant compared with the board cost, the number of cables is not explicitly calculated in this document. However the comparison tables do include the cable cost as well.

The power consumption for a Roach board is estimated at 50 W [5]. However recent measurements showed a power consumption of 25 W according to J. Manley. For the switch 145 W is assumed [7]. For the size of the Roach board 1U is required (in reality a bit higher because of the 10 Gbps connections) and the size of the switch is also 1U.

5.1 The Beamformer

For the beamformer the Roach board is assumed to perform a filterbank operation and a beamformer operation. Both functionalities can be implemented on the same Roach boards. However, since the filterbank operation is done per antenna path and the beamformer operation is done over all the antennas for a specific beam and bandwidth, the data must be routed between both applications. Hence, half of the 10 Gbps interfaces is used for connections to a switch to realize the “transpose” operation, while the other half is used as interface to the next processing stage. Two receivers can be connected to the Roach board via the two differential input interfaces on the Roach board.

Hence, the number of boards to be used equals the number of signal paths divided by two: 12 telescopes * 56 antenna elements * 2 polarizations / 2 = 672 boards.

For the beamforming part, each Roach board receives all the signal paths for a subset of the total bandwidth and produces all 25 beams for a limited bandwidth (the polarization can be parallelized as well). Switches take care of the “transpose operation” required to route a subset of the bandwidth of all signal paths to the Roach boards. Since one switch cannot connect all antenna elements, multiple switches are required. The maximal amount of ports to be used per switch for antenna signals can be calculated such that enough ports are available to transport data from one switch to another in order to realize the “transpose” operation. Assuming the number of effective ports to be used for antenna signals as x , the total number of antenna signals to combine (beamform or correlate) as N_s and the total ports of the switch as N_p , then the following equation must hold: $x + x (1 - x/N_s) = N_p$.

Since the architecture is based on distributing the processing in frequency, each processing unit has to process x/N_s of the total bandwidth. Hence, x/N_s of the total bandwidth can be redistributed in the switch which connects the x signal paths, while the rest of the bandwidth $(1 - x/N_s)$ must be distributed to the switches which are connected to the other antenna signals. Solving the equation for x results in one valid solution: $N_s - \sqrt{N_s (N_s - N_p)}$.

This results for the beamformer application in the use of 112 switches to connect all Roach boards together. However, this number can be minimized when multiple outputs of the same Roach board are connected to different switches. In that way you use the Roach board partly as switch also. For simplicity in this comparison is assumed that the 4 optical interfaces of the switch are sufficient to be used for interconnection in between the switches. In that case in total 84 switches are required. Multiplying the numbers with the cost of each item results in the summary listed in Table 2. The total number of FPGA's required is 672 and the total number of cabinets is 30.

Item	Cost (M\$)	Power (kW)
Board	3.36	16.80
Cables	0.17	
Switch	0.81	12.18
Cooling		28.98
Total	4.34	57.96

Table 2 Cost and power breakdown of the Apertif beamformer using Roach technology

5.2 The Correlator

For the correlator a filterbank operation is assumed to make the final frequency resolution necessary for the Apertif application and a correlator operation is assumed. The correlator can be parallelized in both beams and frequency. Basically 25 parallel correlators are necessary, each for one beam.

The filterbank and correlation operation can be combined in one Roach board. Also for this application the data must be re-ordered in between the filterbank and correlator operation. This is accomplished via switches. To interface with the switches half of the 10 Gbps board interfaces are required. Hence, two 10 Gbps interfaces remain to interface with the beamformer. Since the total number of required 10 Gbps links for each single polarized telescope is 12, in total 12 telescopes * 2 polarizations * 12 / 2 = 144 boards are required. The number of switches necessary to connect the beamformer to the filterbank of the correlator is 20.

The total cost and power is listed in Table 3. Furthermore, in total 7 cabinets are required to house the Apertif correlator with the Roach technology. The total number of required FPGAs is 144. Note that the total cost of the Apertif correlator based on Roach technology was independently estimated also estimated by van Leeuwen et. al. The reported estimation was 2.08 M\$ [6]. However, this number was based on two filterbank stages and explains the factor two differences in cost.

Item	Cost (M\$)	Power (kW)
Board	0.72	3.60
Cables	0.04	
Switch	0.00	2.61
Cooling		6.21
Total	0.76	12.42

Table 3 Cost and power breakdown of the Apertif correlator using Roach technology

6 Implementation with Quinten Technology

The Quinten system will be an integrated subrack. In total 9 Uniboards fit in a 9U 19" subrack. The boards are interconnected to each other via a passive backplane. The board is called a UniBoard (cf. RadioNet UniBoard project) and on each board in total eight FPGAs is integrated [3]. The type of FPGA is not decided yet, but will surpass the type used for this comparison a Xilinx, type XC5VSX95T. The current board design assumes in total 16 external serial 10 Gbps links and 8 times 16 differential lines to interface with a receiver. The UniBoard is split in an input section and output section. The input section is connected to the external "world", while the output section is connected to the backplane [7]. The reasoning behind this is that the applications targeted for the Quinten system have an operation which splits up the band, than a "transpose" operation to re-distribute the data and finally an operation which sums or correlates part of the band for multiple signal paths. The cost breakdown of a board in the Quinten system is listed in Table 4.

Item	Cost (\$)
Board	3500
FPGA	2000
Rest	500
Total board	20000

Table 4 Estimated Quinten board cost breakdown

For the Quinten system in principal no switches are required, unless the number of independent signal paths of 10 Gbps which needs to interact exceeds the 128. In the Apertif application this is not the case. Furthermore for the beamformer both polarisations can be parallelized in multiple Quinten systems and the correlator can be parallelized in independent beams.

The power consumption for a UniBoard is estimated at 250 W (20 W per FPGA and 90 W for the rest of the board). The size of a UniBoard is also 1U and 9 boards can be integrated in one subrack. The total amount of subracks in one cabinet is three.

6.1 The Beamformer

The filterbank operation and beamformer operation can be integrated on one UniBoard. Half of the FPGAs is connected to the differential interfaces and the other half to the serial 10 Gbps interfaces. For the Apertif beamformer the receiver is connected via differential lines to the UniBoard in the Quinten system. On these FPGAs the filterbank operation can be performed. In total four signal paths can be handled per FPGA. From there on the data is redistributed over the boards such that the other half of the FPGAs can perform the beamforming operation using fully the backplane and board interconnects. The 25 beams are exported via the 10 Gbps serial transceivers.

The number of boards required is:

$12 \text{ telescopes} * 56 \text{ antennas} * 2 \text{ polarizations} / 16 = 84$ (in total 16 signal paths can be handled per UniBoard). The summary of the total cost and power is listed in Table 5. In total 4 cabinets are required to house all the hardware. Furthermore also for the Quinten system 672 FPGAs are required.

Item	Cost (M\$)	Power (kW)
Board	1.68	21.00
Cables	0.09	
Switch	0.00	0.00
Cooling		21.00
Total	1.77	42.00

Table 5 Cost and power breakdown of the Apertif beamformer using Quinten technology

6.2 The Correlator

Also for the correlator the UniBoard is split in an input section and output section. For this application the input section is formed by the FPGAs which are connected to the 10 Gbps serial transceivers. These input FPGAs perform the filterbank operation, while the output FPGAs performs the correlation. Again the “transpose” is realized through the board and backplane interconnects.

Each input FPGA can process maximal 4 links of 10 Gbps. Since the total number of required 10 Gbps links for each single polarized telescope is 12, in total $12 \text{ telescopes} * 2 \text{ polarizations} * 12 / 16 = 18$ boards are required.

The cost and power breakdown is given in Table 6. The full Apertif correlator will fit in only one cabinet. Also for this implementation in total 144 FPGAs are necessary.

Item	Cost (M\$)	Power (kW)
Board	0.36	4.50
Cables	0.02	
Switch	0.00	0.00
Cooling		4.50
Total	0.38	9.00

Table 6 Cost and power breakdown of the Apertif correlator using Quinten technology

7 Conclusion

For the Apertif beamformer the final comparison between an implementation with the Roach technology and the Quinten technology is listed in Table 7.

Item	Roach	Quinten	Factor
# switches	84	0	
# boards	672	84	8
# FPGAs	672	672	1
# cables	2688	1344	2
Cost (M\$)	4.3	1.8	2.5
Power (kW)	58.0	42.0	1.4
Size (cabs)	28	4	7

Table 7 Comparison for the Apertif beamformer

The comparison for the Apertif correlator is listed in Table 8. The beamforming requires much more processing than the correlation, which is clearly visible from the cost estimates in the two tables.

Item	Roach	Quinten	Factor
# switches	18	0	
# boards	144	18	8
# FPGAs	144	144	1
# cables	576	288	2.0
Cost (M\$)	0.8	0.4	2.0
Power (kW)	12.4	9.0	1.4
Size (cabs)	6	1	6

Table 8 Comparison for the Apertif correlator

The two tables above clearly show that for large scale beamforming and correlation implementations the hardware costs for the Quinten approach are much lower than for the Roach approach. Also, the operational cost (power consumption) using the Quinten architecture is much lower. Finally, the physical size of a Quinten based system would be nearly an order of magnitude smaller than using a Roach based system.

Summarizing, the tradeoffs between Quinten and Roach are implementation speed for which a Roach approach seems a better choice, and cost, physical size and power consumption for which Quinten seems a better choice.

8 References

- [1] A.R. Thompson, J.M. Moran, G.W. Swenson, Interferometry and Synthesis in Radio Astronomy, 2001.
- [2] A.W. Gunst, G.W. Schoonderbeek, E. Kooistra, Quinten Architectural Design, ASTRON-RP-303, January 2009, Dwingeloo, the Netherlands.
- [3] G.W. Schoonderbeek, S. Zwier, Quinten Board Design, ASTRON-RP-xxx, January 2009, Dwingeloo, the Netherlands.
- [4] <http://casper.berkeley.edu/>
- [5] A. Parsons, D. Backer, H. Chen, P. Droz, T. Filiba, D. MacMahon, J. Manley, P. McMahon, A. Parsa, D. Werthimer, M. Wright, A scalable Correlator Architecture Based on Modular FPGA Hardware and Data Packetization, Submitted for Publication to: IEEE Transactions on Signal Processing, February 2008.
- [6] J. van Leeuwen, J. Manley, Roach@Apertif, 2008-1.xls file.
- [7] Fujitsu Computer Products of America, NGP Products, Powerpoint presentation held in Berkeley in 2008.