SKA Project Series
Describing LFAA using SysML

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Abstract

During the preparation of the documentation for the SKA Low Frequency Aperture Array, a system modelling tool has been used to aid the system design. The tool adopts the SysML graphics language to describe the system product breakdown structure, to identify the internal and external connection between its elements, the interfaces that characterise the system, and to describe the functions and the data flow associated with each element. The derived diagrams were used in the documents being prepared for the instrument critical design review.

The main advantage in applying such an approach is the ease of modification and maintenance of the documentation. As the elements composing the system and their relations are defined inside the abstract model, any change is automatically reflected in a consistent ways in all diagrams describing the instrument.

1 Introduction

The Square Kilometre Array telescope (SKA) is an interferometric radiotelescope, composed of hundreds of individual elements, operating between 50 MHz and 16 GHz. In the first stage (SKA1) it will consist of two instruments: SKA1-LOW, composed of 512 aperture arrays in the Australian desert, and operating between 50 and 350 MHz, and SKA1-MID, made up by 192 dishes, operating above 350 MHz in South Africa.

SKA is not only vast in scale, covering huge tracts of the desert regions in Africa and Australia, but is also one of the most complex science projects ever conceived. With SKA, a global effort involving thousands of engineers, scientists, astronomers and construction specialists will work together to deliver a truly remarkable telescope [1].

SKA1-LOW aperture array element (Low Frequency Aperture Array, or LFAA) is itself a very complex system. Each of the 512 arrays (stations) is composed of 256 individual dual polarization antennas. The received signals must be digitized, transported to a central building and combined into one or more station beams. LFAA was initially designed using conventional system engineering methodologies, by separate teams. While working on the documentation for LFAA, it became apparent that it is necessary the use of a unique tool for the high level definition of the system. The Resolution Teams organised by the SKAO (SKA Office) to coordinate the design work decided to use a Model Based System Engineering (MBSE) tool. In particular the SysML (System Modelling Language) modelling language, using the No Magic Cameo Systems Modeler has been applied.

One of the main advantages in using SysML is its interdisciplinary approach [2]. It can be applied indiscriminately from very small devices to extremely large and complex systems, like SKA. It supports a hierarchic description: work performed on single elements can be directly merged in the larger system. Other advantages are connected to the project development cycle: customer requirements and main project functionalities are identified from its very beginning; technical and economical aspects are considered in parallel during the whole design phase and at different scale level; they can therefore be controlled more efficiently.

The application of such a tool, in parallel to a normal design one, allows to represent all the information related to a system in dynamic diagrams. SysML allows the design to be represented using several kind of diagrams. Each diagram highlights only some particular aspects of the project [3]. In very large projects requirements and information related to the whole system are generally split into several documents so it becomes difficult to keep them all consistently updated. With SysML all the diagrams are inter-related: as these diagrams represent a unique underlying model, they consistently describes the elements and relations in the project [4], and therefore a change in a diagram is reflected in all the connected ones.

In this report we describe this methodology as it has been applied to LFAA. Main analysis steps are described, with examples of the diagrams that illustrate the model.

The whole analysis has been used in the SKA1-LFAA Architecture Design Document, and in the Detailed Design Documents for the LFAA sub-elements.

2 Element decomposition analysis

The work of describing LFAA using SysML began when the project was already started. The main job has been therefore to collect, in a unique model and in a consistent way, all the work already done and realised by different teams.

The first step was the preparation of a blocks tree, representing the LFAA product breakdown structure (PBS). This PBS was realised through the preparation of block definition diagrams (bdd), which highlights the constituent blocks of the system in a hierarchical tree.

All the diagrams presented in this section are bdd, which describe the system architecture and the hierarchy in terms of blocks and sub-blocks. The bdd can include blocks of any type including software, hardware, etc. It is the base of the system structural decomposition, provides the contents inventory and the quantity of each part [5], and is the base input in procurement lists, fault analysis, costing and power, etc.

The system model may contain the full structural decomposition, starting from the whole telescope (Level 1 of the tree). In our case, as we focused on the LFAA sub-element (Level 2), our model contains a very crude decomposition structure for the whole and details only the other Level 2 LFAA elements without further analysis. It will however be possible to directly merge this model in the SysML description for the whole telescope. It is the designer decision the choice of the levels to be shown in the diagrams, which depends on the type of information that need to be displayed and the environment in which the diagrams will be inserted. Depending on the level of details required, a bdd may stop at an high level of definition, showing the "macro elements" composing a system, or may arrive to very low level, showing all the single elements included in the system.

Usually the diagrams are created showing a limited number of levels, usually just three or four levels, in oder for the diagrams produced to be be easily readable, as has been done in Figure 1, Figure 2 and Figure 3. This is only a stylistic choice since the entire model remains the same and it is unique. Diagrams represent only three different views which highlight three different aspects of the same model.

The first diagram developed highlights the element that constitute LFAA up to level 4, as displayed in Figure 1. In this diagram we used different colours to differentiate more in details the varioua level 3 elements and sub-elements.

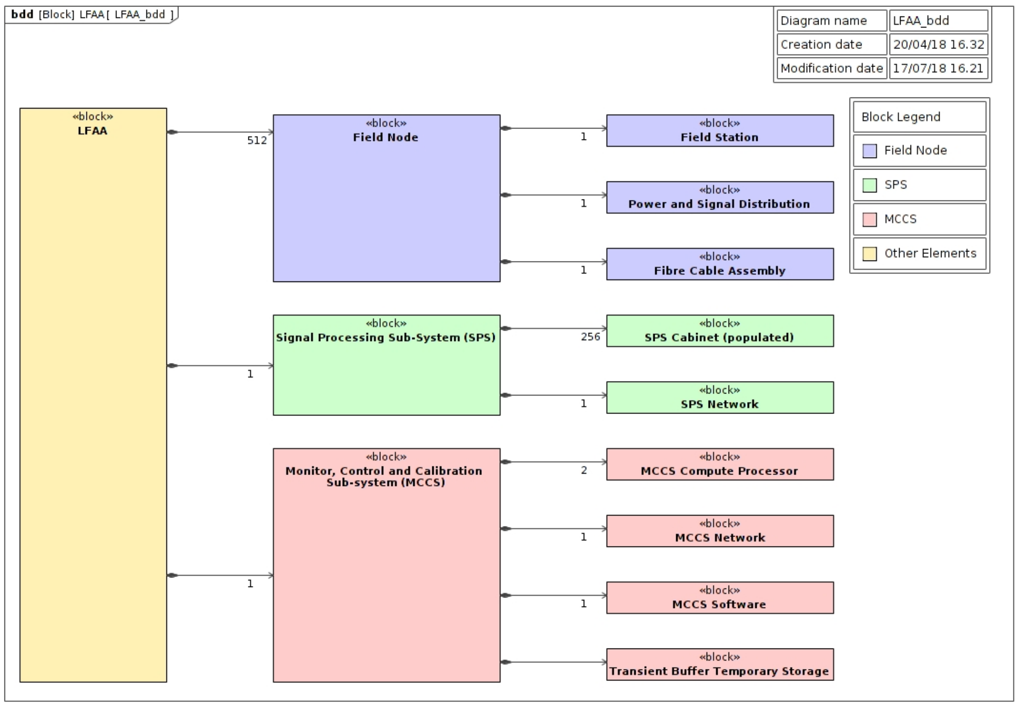

Figure 1: LFAA block definition diagram

Following this top-level static decomposition of LFAA, additional digrams have been developed that flow down more in details in the composition of the LFAA system. For example, Figure 2 starts from L4 component `SPS Cabinet (populated)`, which is a sub-element of the `Signal Processing Subsystem` (SPS) element, and flows down until L7 elements. Similar diagrams have been created also for the other LFAA components, i.e. the `Field Node` (FN) and the `Monitoring, Control and Calibration Sub-system` (MCCS).

SPS cabinet is the main component of the Signal Processing Sub-system, which receives the radio signals from the individual antennas, convert them to a digital format and processes them into station beams. Identical cabinets are used in the core stations (stations within 10 km form the array centre, processed in a single building) and in remote stations, with each cabinet implementing the SPS functionality for two stations. SPS cabinet is composed of the following elements [6]:

- The cabinet chassis, holding all other components
- Two 40 Gbps 32 port switches, implementing a single 40 Gbps Ethernet network for science data
- One 1Gbps Ethernet switch, for the control and management network
- The Cabinet Management Board (CMB)
- The AC power distribution system, distributing AC power to all Level 4 components under CMB control
- The Cooling System, to remove heat from other level 4 components
- Four TPM sub-racks, processing signals from 128 antennas each
- Required cabling.

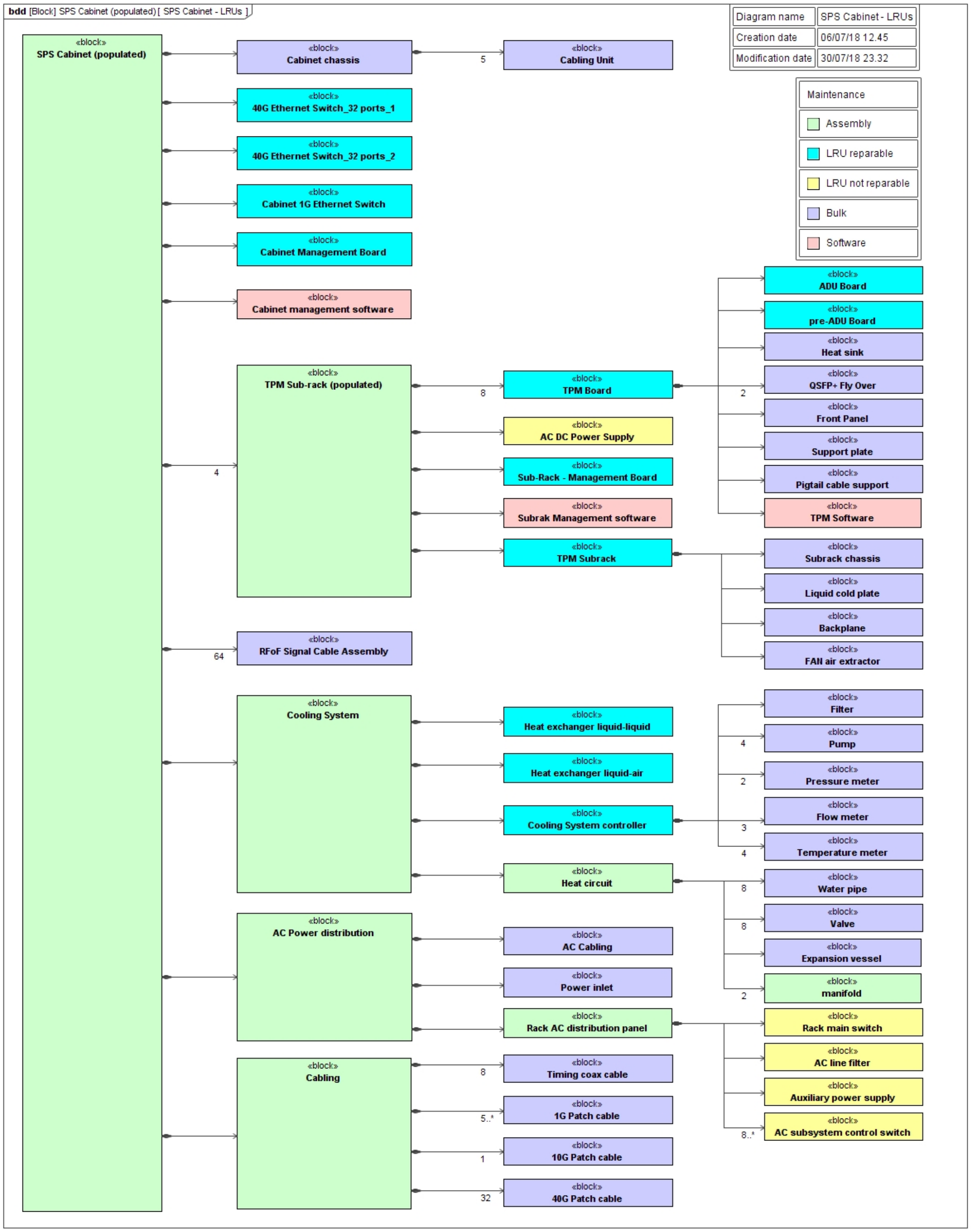

Figure 2: SPS Cabinet PBS with LRUs

It is possible to attach properties to each block. In our analysis we were interested in identifying the Line Replacement Units (LRUs) of LFAA, i.e. those elements which can be replaced as a single unit by the operator, in case of a fault. Their individuation is important in the view of large project since it allows a comprehensive organisation of the maintenance. For example faults must be identified and isolated up to one LRU, and spare parts maintained, in order for the operator to be able to quickly identify and replace it, and to restore the functionality of the system.

Figure 2 displays the LRUs of the SPS Cabinet, which are coloured depending on their properties. This diagrams has the double task of showing a deeper detail level of the LFAA components in the SPS and to highlight which are the components of the systems that could be replaced entirely and therefore for which could be necessary to have spare parts. Furthermore, the LRUs have been divided into those that are reparable and those that cannot be, with corresponding different inventory requirements.

The LRUs include [6]:

- All rack mounted items. The TPM sub-racks contain LRU boards, but can be replaced as a whole unit, after removing the LRU boards.
- Cooling main unit (liquid-to-liquid) and associated sub-elements, contained in a standard rack mounted cabinet.
- Liquid-to-air heat exchanger mounted on the side space of the cabinet
- All electric power distribution elements, mounted on DIN rails
- All cabling
- Water pipes and valves

The level of detail until which the system engineer decide to flow down depends on the scope of the documentation in which the diagram is used. In Figure 2 the structure of part of the system is analysed until level seven, but to analyze individual elements it can be flow down to lower levels. An example of an element which requires such an analysis is the L6 element Tile Processing Board (`TPM board`), in Figure 3, which flows down to L9. The TPM is the main signal processing element, and it is in itself a complex element. Lowest level elements represent the signal processing firmware, which is further analyzed, also using SysML, in section 5 in this report.

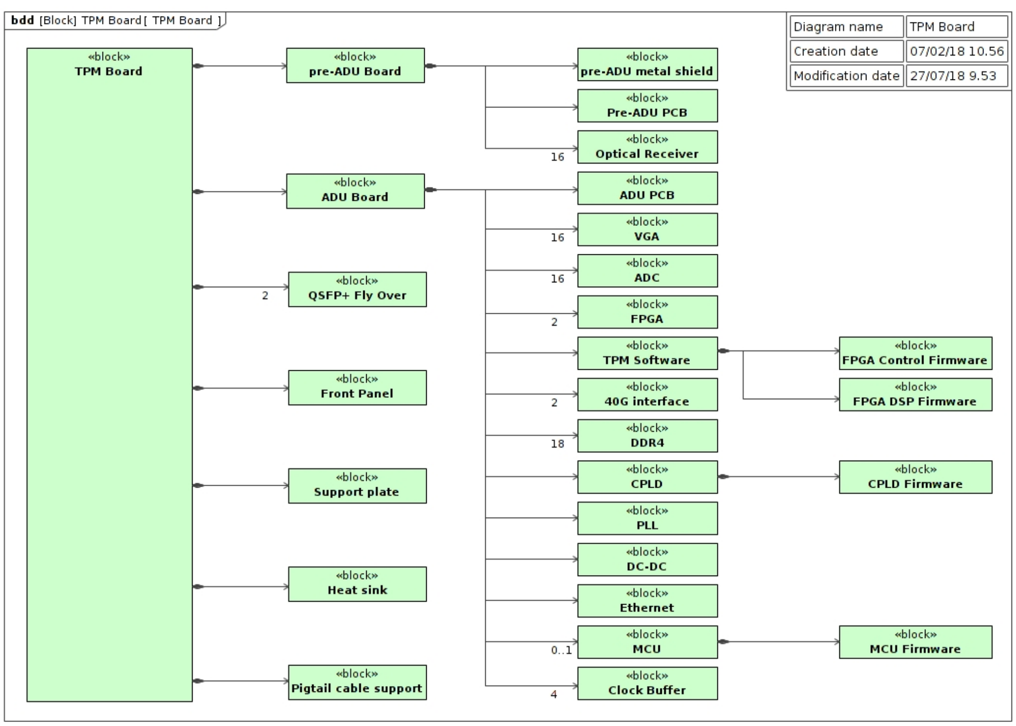

Figure 3: TPM board PBS

3 Interfaces between elements

All the diagrams presented in this section and in the following ones are internal block diagrams (ibd). They show the internal structure and the connections between blocks in terms of properties and links between them. They are instantiated using the blocks defined in the block definition diagram and provide an internal view of the system, to represent the final assembly of all blocks within the main system block. [5]

With large project, it is fundamental to analyse the interfaces which characterise the system. The ibd allows to identify all the required interfaces and the elements (end points) which are involved in the interface definition. The interface itself is not contained in the model, but can be referenced as an external document.

The interfaces can be either internal or external to the system. Internal interface are those that connect only sub-elements, i.e., for LFAA, the SPS, FN and MCCS. The external interfaces are those that connect LFAA with other elements: the infrastructure of the telescope site (Australian Infrastructure, or INAU), the Central Signal Processor (CSP) and the Signal and Data Transport (SaDT) subsystems.

Figure 4 shows all the LFAA internal and external interfaces. This diagram analysed the interfaces among all the elements and subelements, both internal and external, but is too complicate to give, at a first glance, a clear image of all the connections. It is further complicated by the fact that part of the SPS cabinets will be hosted inside the Central Processing Facility (CPF), while others will be hosted in separate buildings in the field (Remote Processing Facilities, or RPFs), with corresponding different interfaces. [1]

For this reason additional diagrams, have been developed, in order to analyse the interfaces corresponding to each LFAA component. Figure 5 highlights only the internal interfaces connecting the Signal Processing Sub-system and the Field Node. The diagram shows which elements and sub-elements of SPS and FN are involved in the interfaces and the name of each interface.

Figure 6 analyses more in details all the interfaces which characterise the Signal Processing Sub-system, for the SPS cabinets site in the Central Processing Facility (CPF), both internal and external.

All the interfaces included in Figure 6 are also summarised in Table 1.

Interface	Type	Internal/External
I.S1L.LFAA_INAU.004	Mechanical	External
I.S1L.LFAA_INAU.005	Power	External
I.S1L.LFAA_INAU.008	Thermal	External
I.S1L.LFAA_INAU.009	Mechanical	External
I.S1L.SADT_LFAA.001	Electrical	External
I.S1L.SADT_LFAA.002	Electrical	External
I.S1L.SPS_FN.001	Optical	Internal
I.S1L.SPS_FN.002	Optical	Internal
I.S1L.SPS_FN.003	Mechanical	Internal
I.S1L.MCCS_SPS.001	Optical	Internal
I.S1L.MCCS_SPS.003	Logical	Internal
I.S1L.LFAA_CSP.001	Optical	External

Table 1: Internal and external interfaces for SPS

[1]The CPF is a screened room which houses the SPS for stations in a 10 km array core, as well as other systems, such as the SaDT timing and network, the CSP correlator and LFAA MCCS. [6]

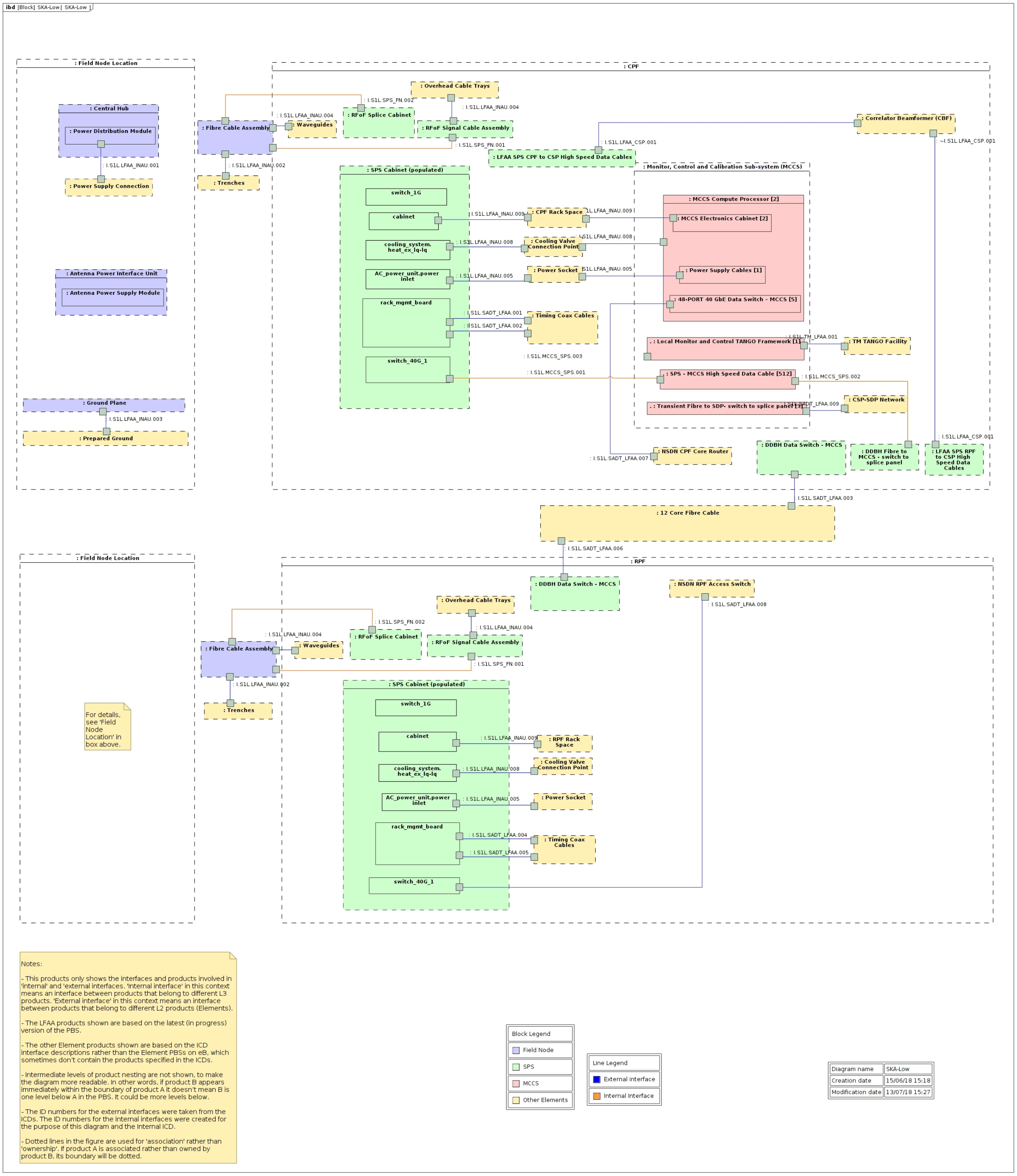

Figure 4: SKA LFAA Interface Diagram

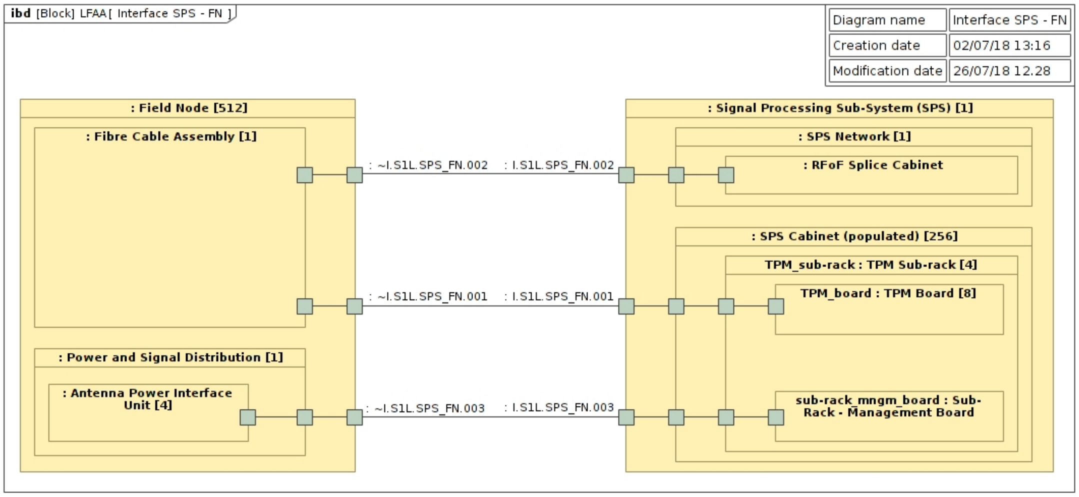

Figure 5: Interface Diagram between L3 elements, SPS and FN

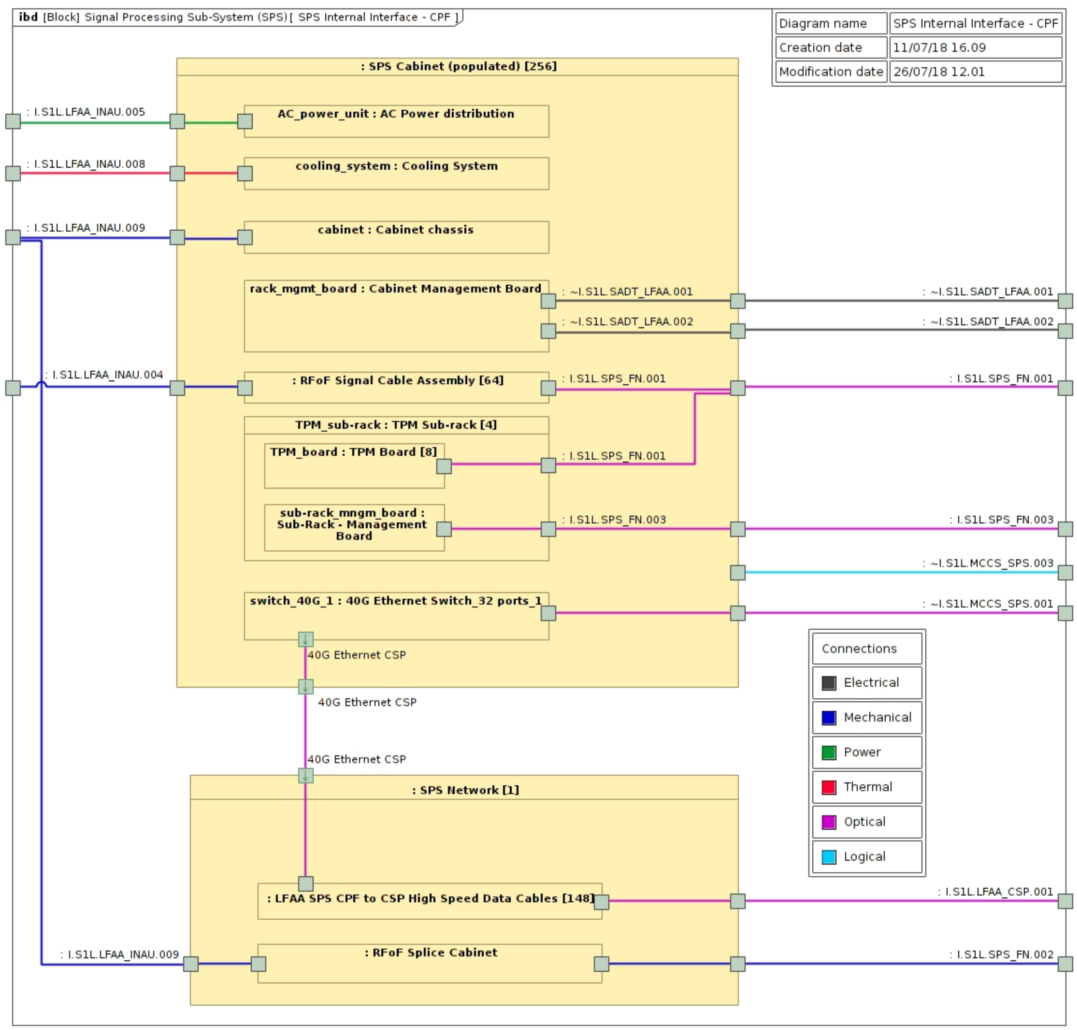

Figure 6: SPS Interface between L4 elements - Central Processing Facility

4 Data flow among elements

Internal block diagrams can also be used to describe the physical interconnection between elements and the flow of information or physical quantities (heat, power) among them. As an example, the ibd for a SPS Cabinet is shown. The main components of the SPS Cabinet have been highlighted in Chapter 2. In this section three diagrams are presented, they analyse in detail the data flow and the connections between the elements composing respectively the Rack, the Sub-rack and the TPM. Going through these diagrams the analysis is gradually more detailed, to represent an example on how such an analysis may arrive at the required level of detail.

4.1 Rack

Figure 7 represents the first level of detail, i.e. the data flow and connections between the elements composing the Rack. Different colours have been used to distinguish between the nature of the interface (mechanical, thermal, power, signal).

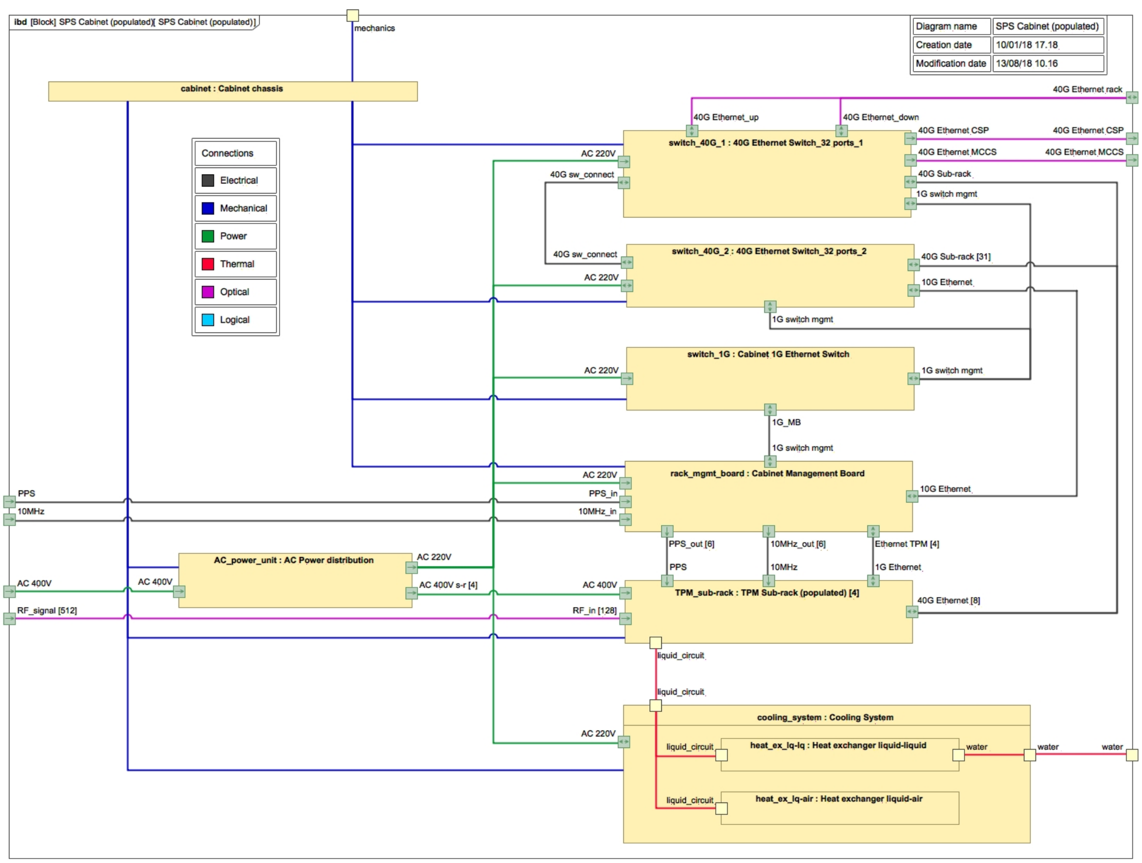

Figure 7: Internal block diagram of the SPS Cabinet

Blue line - mechanical connections

The cabinet chassis is mechanically connected with all the elements inside the SPS Cabinet. Each Rack contains:

- 2 x 40G Ethernet Switch
- 1G Ethernet Switch
- Cabinet management board
- AC power distribution
- 4 x TPM sub-rack

- Cooling system

Green line - power connections

The AC power distribution is fed by an AC current at 400V, 3 phase, and provides power to the four TPM Sub-racks. All the other elements, i.e. the two 40G Ethernet Switch, the 1G Ethernet Switch, the Cabinet management board and the cooling system are fed with a AC electrical current at 220 V.

Grey line - electrical connections

These lines represent the distribution of the timing signals, and of the data network (Ethernet), using copper wire distribution. The electrical signals, PPS and 10 MHz enter the cabinet through the Cabinet management board, which distributes these signals to the four TPMs. Furthermore, the Cabinet management board is connected to the TPM Sub-racks with 1G Ethernet signal and with one of the two 40G Ethernet Switch with a 10G Ethernet signal. The two 40G Ethernet switch have also a direct connection between each and are both connected with the 1G ethernet switch and also with the TPM Sub-racks through 40G Ethernet connections.

Lilac line - optical connections

These lines represent optical signals, both relative to the incoming radio signals (analog) and broadband Ethernet. One of the 40G Ethernet switch is connected with the previous and the successive rack and also with the CSP and the MCCS. Optical fibres also enter direct the TPM Sub-racks with the RF signal from the antennas.

Red line - thermal connections

The liquid circuit directly removes the heat from the TPM Sub-racks. A liquid-air heat exchanger removes heat form the ambient air in the cabinet, and a liquid-liquid heat exchanger transfers the heat from the cabinet liquid circuit to the infrastructure provided cooling system.

4.2 Sub-rack

The sub-rack is the main component of the rack. Since the sub-rack is a complex object, the same type of analysis adopted for the cabinet has been carried out for its internal connections. It is highlighted in Figure 8.

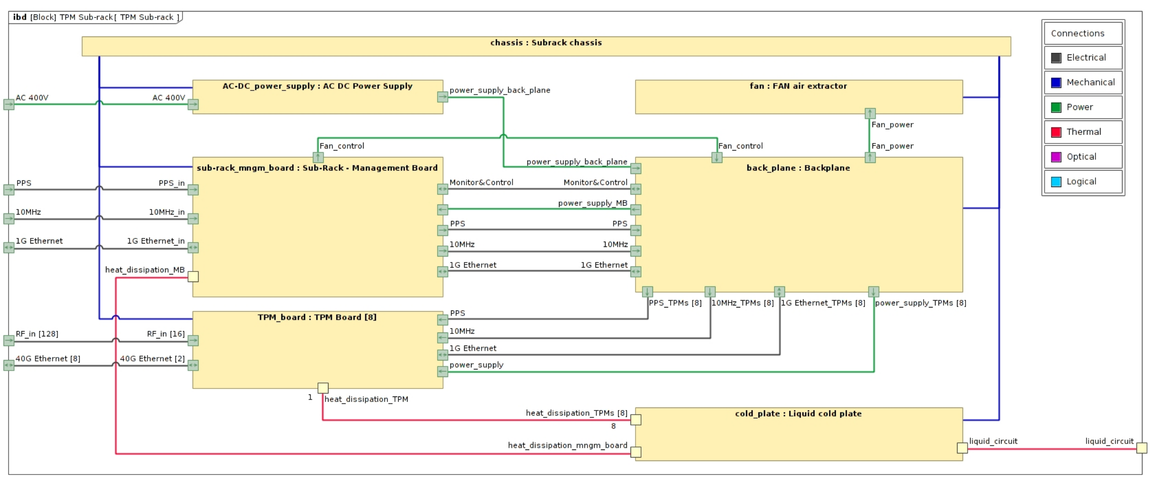

Figure 8: Internal block diagram of the TPM Sub-rack

Blue line - mechanical connections

It is made by a chassis that in mechanically connected with all the elements inside. Each sub-rack contains:

- 4 x TPM boards
- Sub-rack management board
- Backplane
- AC DC power supply
- FAN air extractor

- Liquid cold plate

Green line - power connections

The power supply unit is fed by an AC current at 400 V and it provides the power to the Backplane. The Backplane in turn fed with electrical power the fans, the Sub-rack management board and the four TPMs.

Grey line - electrical connections

The electrical signals, PPS, 10 MHz and 1G Ethernet, enter the sub-racks through the Sub-rack management board, which in turn transmits these signals to the backplane, and from the backplane to the TPMs. Also the RF signal enters the TPMs, where is processed. Each TPM board produces 2x40G Ethernet signals that go outside the Sub-rack. There are also two control signals that go from the Management Board to the backplane and to the fan for Monitor and Control.

Red line - thermal connections

The Cold Plate is connected through heat sink to the four TPMs and to the Sub-rack management board to remove the heat produced by the boards directly. On the other side, it is connected to Rack liquid circuit for the heat removal.

4.3 TPM

The TPM is one of the most complex assembly as a LFAA LRU component and it is the main processing component within the SKA-LFAA element. It is a hybrid analogue/digital module that receives 32 analogue input signals coming from 16 dual polarization antennas (one SKA tile) via RFoF links and contributes with the cooperation of other tile processors to form the station beam. In fact, since each TPM computes the beam of one tile and sums the incoming partial beam from previous tile processors with the tile beam formed locally, when connecting more tile processors in a daisy chain the output of the last will be the beam of the station.

The TPM is mainly composed of two boards: the pre-ADU board and the ADU board (Analog to Digital Unit). The pre-ADU boards is devoted to optical-electrical conversion, filtering, amplification and equalization of 32 analogue signals. ADU board has the following tasks: analogue to digital conversion, polyphase filtering, application of calibration and beamforming coefficients, sum of all 32 signals to form the tile beam (local), sum the tile beam with the incoming partial station beam and transmission of the data to the network (switch). [6]

Figure 9 shows the internal connection in the TPM board and the data flow internal to the board.

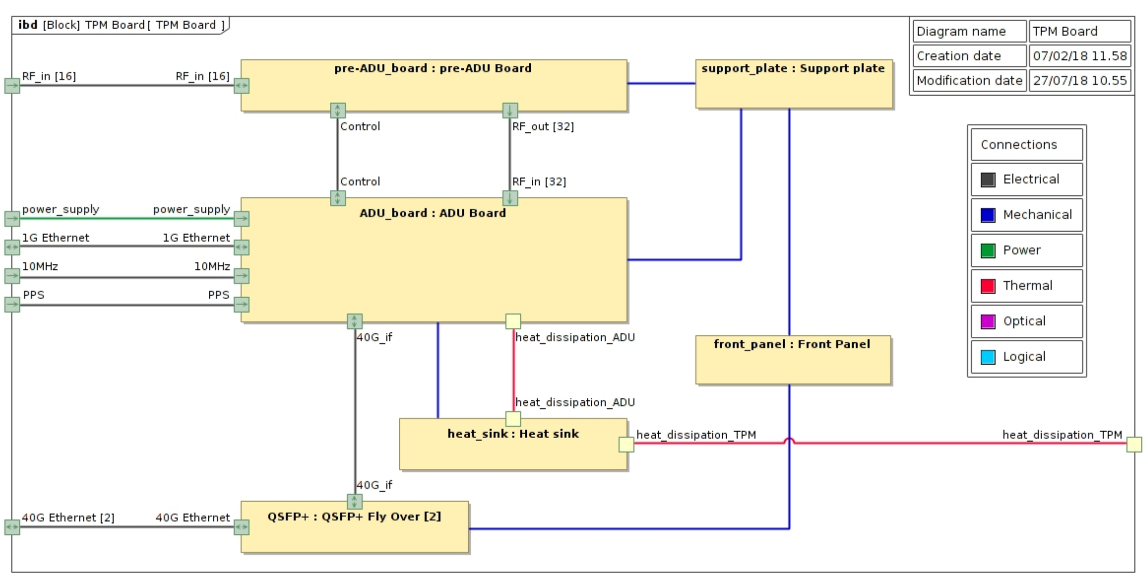

Figure 9: Internal block diagram of the TPM Board

Blue line - mechanical connections

The support plate is mechanically connected with the pre-ADU and ADU boards and with the front panel. The front panel works as support for the QSFP+; while the heat sinks are mechanically connected to the ADU board for the heat removal.

Grey line - electrical connections

The electrical signals, PPS, 10 MHz and 1G Ethernet, enter directly the ADU board while the RF signal enters the TPM through the pre-ADU board, then passes to the ADU board where is processed. ADU and pre-ADU boards have also a control signal connection between them, for the control of the process. The output of the ADU boards is a 40 G signal that through the QSFP+ connector comes out of the TPM.

Red line - thermal connections

The heat sinks remove the heat directly form the ADU boards and they are part of the Sub-rack heat dissipation circuit.

5 Firmware

The same analysis has been performed for the firmware installed on the TPM. This aspect shows once more the interdisciplinary behaviour of SysML, which can be also used to anayze the software installed in the board, modelling firmware components.

The firmware is organised in layers. An external input/output ring provides standard interfaces to the on-board peripherals. Inside this ring the DSP processing layer is hosted. This separates all issues related to the particular board, and eases hardware upgrades.

The DSP structure for the prototype firmware is shown in Figure 10. Different clock domains for the signals are highlighted with different colours of the connecting lines between the elements. On the left the main signal processing chain is shown. The sample test generator takes the samples from the ADC interface, optionally substituting them with an artificial test signal. Samples are then channelized, calibrated and beamformed in a tile beam, and combined with tile beams from other TPMs to form a station beam.

Modules on the right perform monitor and control functions [7]. The Total power and RFI detector monitors broadband signal level, and identifies sudden increases in power level as RFI. The LMC generator collects sample blocks at different processing stages for remote monitor, and generates calibration spigots. The LMC integrator computes integrated spectra, with a resolution of one LFAA channel. Both sample blocks and spectra are sent to MCCS as SPEAD formatted UDP packets, either on the 1Gbit/second monitor link (`axi4s_s_arr`) or on the 40G high speed data link (`udp_tx_arr`) [7].

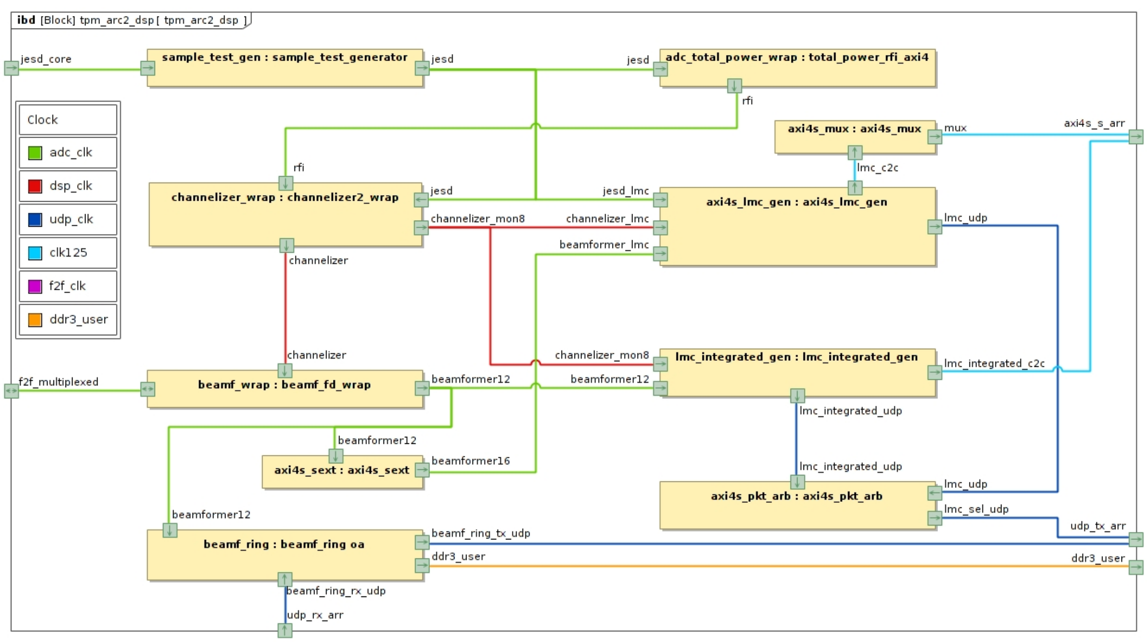

Figure 10: DSP Firmware layer block diagram

6 Conclusions

The use of SysML to approach such a large system has several advantages for the preparation of the project documentations. It allows to have a comprehensive model that covers many of the aspects of the systems and highlights the interface between each part, grouping all these information in the same location.

Furthermore, during the preparations of the diagrams missing connections between elements have been highlighted. As sub-elements that were in charge at different working groups, some assumptions on interfaces and required interconnections were not correctly and coherently stated. In this way, the discussion between different groups has been promoted in order to have a more comprehensive and inclusive model, avoiding inconsistencies.

List of acronyms

ADU: Analog to Digital Unit

bdd: block definition diagram

CMB: Cabinet Management Board

CPF: Central Processing Facility

CSP: Central Signal Processor

DSP: Digital Signal Processing

FN: Field Node

INAU: Infrastructure Australia

ibd: internal block diagram

ICD: Interface Control Document

IICD: Internal Interface Control Document

LFAA: Low Frequency Aperture Array Element or Consortium

LRUs: Line Replacement Units

MBSE: Model Based System Engineering

MCCS: Monitor, Control and Calibration Sub-System

PBS: Product Breakdown Structure

SaDT: Signal and Data Transport

SPS: Signal Processing Sub-system

SysML: System Modelling Language

SKA: Square Kilometre Array

SKAO: SKA Organization (or office)

TPM: Tile Processing Module

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