The SKA from a Communications Infrastructure Perspective

Charles Smith
Commonwealth Scientific and Industrial Research Organisation
Cnr., Vimiera and Pembroke Roads
Marsfield, New South Wales 2122
Australia
charles.smith@csiro.au

Abstract—The Square Kilometre Array (SKA) is a global science project to construct and operate a geographically distributed radio telescope. To meet the technical requirements demanded by the science goals, the SKA will be implemented using thousands of sensors, of a several different types. The types of sensors proposed include traditional single-pixel feeds, sparse aperture arrays and the more advanced dense aperture arrays and phased array feeds. Each sensor type has varying sampling rates, but all have extremely strict timing requirements and require massive data transmission and computational resources for the tasks of beam-forming, correlation, post processing, analysis and archiving of the observation datasets.

Consequently, a large component of the SKA will be the communications infrastructure required to interconnect the sensors and other elements of the system. Industry standards based scalable communications architectures for the SKA are introduced that will allow for the progressive installation, maintenance and phased upgrade of the instruments’ sub-systems and identify possible interface points in the communications hierarchy where commercial-off-the-shelf (COTS) products and services can be adopted in the SKA data and control planes.

Table of Contents
1. Introduction ......................................................... 1
2. SKA Communications Sub-Systems ..................... 2
3. Sensor Technologies.................................................... 2
4. Selecting a COTS Interface for SKA Phase 1 Sensors ................................................................. 3
5. Ethernet as the COTS Interface ......................... 4
6. Worked Example for SKA Phase 1 Transmission Capacities ......................................................... 5
7. Conclusions ................................................................. 6
8. References ................................................................. 7

1. Introduction

The SKA design process can be seen as “an exercise in optimizing the transport and processing of very large volumes of data: a perspective likely to appeal to industry and other associates operating outside the astronomy arena.”[2] and; “It is desirable to be able to minimize design and construction costs by using commercially available equipment where possible, to exploit Moore’s law and available commercial products.”[1]

The communications industry is dominated by the requirement for products and technologies from multiple vendors to interoperate with each other, and to continually meet demands for increased performance, particularly regarding transmission bandwidth and capacity. This is achieved through a strong culture of standards definition and adoption, based around internationally recognised standards bodies including the Institute for Electrical Engineers (IEEE), International Telecommunications Union (ITU) and the Internet Engineering Task Force (IETF). In addition to ensuring interoperability, standards are crucial in driving the adoption of a given technology by customers, which increases the market size for that technology, and hence reduces the unit cost of products based on that standard. A further consequence to the communications industry of widespread adoption of a particular technology standard is the need to ensure that future technology standards remain backwards compatible with existing standards, otherwise adoption of the new standard will not be widespread, and hence will not achieve the desired reduction in unit cost.

A method that the SKA can leverage these attributes is to adopt a design principle to align the SKA hardware and software interface specifications with those in widespread use and defined by the communications industry standards bodies. This principle is most critical when considering connections between elements of the SKA that can leverage COTS solutions from industry. It is also recognised that there may be requirements where existing standards cannot assist in achieving a scientific goal of the SKA and a custom or purpose-built solution will be appropriate.

More broadly, industry-wide standards also minimise commercial risk by offering multiple avenues to source products and provide a wide support base for maintenance.

We aim to identify where the insertion points for the adoption of standards based communications infrastructure can be applied to the SKA, and analyse the suitability of such standards for supporting the SKA science goals.
2. SKA COMMUNICATIONS SUB-SYSTEMS

At a systems level the SKA needs to build and maintain four very different network infrastructures, these being:

- A sensor data plane network. In this document we aim to address the interface connectivity for, and adoption of, industry standards for this network.

- A timing distribution network providing extremely accurate timing and synchronization signals to the sensors, beam formers and correlator. The timing distribution network is outside the scope of this document.

- A high availability monitor, control and operational management network. An architectural model for an industry standards based monitor & control infrastructure has been presented in [7].

- A hierarchical supercomputing and archival data and storage capability for post-processing, data sharing, scientific analysis and Internet interconnectivity.

3. SENSOR TECHNOLOGIES

The design of the sensors for the SKA are clearly within the scientific domain as they are finely tuned instruments developed for the particular task at hand on the basis of leading edge science. However, the digital output streams of such sensors should be aligned to the “industry standards” principle in order to gain the cost and support advantages from the volume markets provided by component suppliers and manufacturing houses.

There are four distinct sensor technologies proposed for the SKA:

- SKA Phase 1 includes Single Pixel Feed (SPF) dishes sampling the 450 MHz - 3 GHz bands with data rates from each dish estimated to be 24Gb s⁻¹.[3] Further development, as a new technology innovation option for SKA Phases 2 and 3, seeks to extend the sampling band to 300 MHz - 3 GHz while extending the data capture rates from each of the 3000 dishes up to 216 Gb s⁻¹.[3] Figure 1 outlines the custom interfaces and downstream data rates with possible connections to COTS interfaces for SPF dishes for SKA Phase 1.

Figure 1: SPF A-D & COTS Interface

- SKA Phase 1 also includes Sparse Aperture Arrays (SAA) sampling the 70-450 MHz bands with data output from each of the 50 stations estimated to be 1.216 Tb s⁻¹.[3] Figure 2 outlines the custom interfaces and downstream data rates with possible connections to COTS interfaces for SAA sensors.

Figure 2: SAA A-D & COTS Interface

- SKA Phase 1 will consider as a new technology innovation option, Phased Array Feeds (PAF) on
the dishes sampling the 600 MHz – 1.5 GHz band with post beamformed data rates from each in the order of 928.8 Gb s\(^{-1}\).[3] Figure 3 outlines the custom interfaces and downstream data rates with possible connections to COTS interfaces for PAF dishes.

![PAF A-D & COTS Interface](image)

**Figure 3: PAF A-D & COTS Interface**

- SKA Phase 2 will consider as a new technology innovation option, Dense Aperture Arrays (DAA) sampling the 400 MHz – 1.4 GHz band with post beamformed data rates from each of the 250 stations in the order of 16.8 Tb s\(^{-1}\).[3]

SKA Phase 1 will have 50% of sensors within 500m, 20% within 2500m, and the remaining 30% within 100km of the core observation area site. There will be separate correlation aggregation requirements for the SPF dish array, SAA stations and optionally the PAF dish array allowing for each to be individually housed and managed.

SKA Phases 2 and 3 require sensor outputs within a sampling band to be transmitted to central correlation facilities. The core observation area will hold 80% of the sensors with the remaining 20% located in spiral arcs ranging from 100km to 3000km from the central location.

Most sensors will be located in remote environments and sited to minimize radio interference.

### 4. Selecting a COTS Interface for SKA Phase 1 Sensors

Industry standards for digital data transmission that can satisfy the sampling requirement rates are SONET/SDH, Ethernet, and Fibre Channel. They each have the capabilities to support the individual streams from sensors with interface addressing, multiplexing and aggregation to identify, encapsulate and reliably transmit the data. They are all supported in Local Area Networks (LAN), Wide Area Network (WAN) aggregation interconnects and capable of long haul transmission via DWDM systems.

The Industry standard Infiniband protocol and interface is currently limited to high-speed interconnections between nodes within close proximity and Data Centres. It is a reasonable choice to investigate for use within the SKA correlation and supercomputing environments. It is not an appropriate choice for the sensor to COTS interface given its distance limitations & current requirement to be subsequently bridged to other COTS technologies for WAN transmission.

For all sensor technologies, bridges between the streaming sensors and COTS transmission interfaces will need to be developed. An approach to accommodate lower transmission data rates from the sensor stream would be for the implementation of a buffering mechanism to support the aggregation of multiple 10G, 40G or 100G lower speed interfaces to service the higher sensor sampling rates.

Minimising the number of transmission COTS Interfaces can be achieved via statistical multiplexing in SONET/SDH. However the additional overhead involved given the direct 4:1 relationship in the SDH hierarchy can not be regained unless a higher layer protocol is implemented. The higher layer protocol would need to provide a non-blocking buffering, aggregation and switching capability of multiple services onto a high speed 40G uplink. For standards based solution a layer 3 routing capability is required. COTS equipment is available at the SONET/SDH level that provides this functionality, however the method is non-standards based and vendor specific. Evolving standards for SONET/SDH for 160G have not been formally proposed to the ITU at this time.

Ethernet and Fibre Channel non-blocking switching and aggregation provides standards based mechanisms using quality of service, inter-frame gaps and port buffering to maximise the average inbound frame rates to the aggregated higher speed 40G or 100G outbound interfaces.

As an example a 10GigE or 10G FC standards based interface for a PAF beam would allow for the under-subscription capacity to be regained upstream of the transmission interface by selecting a Ethernet or FC switch as the COTS interconnect. Figure 4 shows the data flow and resultant transmission capacities for an SKA Phase 1 PAF.
Figure 4: PAF FC or Ethernet Interface

Figure 5 shows possible configurations using frame based Ethernet or Fiber Channel vs. SONET/SDH. The additional bandwidth lost if 40G SONET is used for transmission is 10G if as 40G transmission option is selected. The 15G when using 40G transmission, or 5G when using 10G transmission excess cannot be regained unless the traffic is forwarded to a higher layer routing protocol or via proprietary single vendor solutions within the MUX is employed.

Figure 5: SPF Digital Transmission Options

Selecting 10GbE as a standards based interface for a PAF 7Gbs\(^1\) beam allows for the under-subscription capacity to be regained in a switching fabric if Ethernet or Fibre Channel is chosen. Figure 6 and 7 show the port options when using SONET/SDU, Ethernet or FC for the PAF and SAA configurations.

Figure 6: PAF Digital Transmission Options

Fibre Channel suits simple aggregation functions but needs to be planned and expanded very carefully as the native protocol is blocking based. The standard demands a transmitted frame be delivered and will block other traffic until it has been delivered rather than drop the frame as Ethernet does. This does guarantee delivery of every frame however if there is an imbalance in the system then the link will block. The buffer credit mechanism is used to offset this issue, however it requires careful design of each link in the network and which varies based upon distance and propagation.

Figure 7: SAA Digital Transmission Options

Ethernet provides for a common Layer 2 interface across all sensor types as described in the section 4. It caters for individual sensors used in SPF’s, multiple sensor beam-forming aggregation tasks in SAA’s and PAF’s and resultant correlation compute tasks. Expected growth in sensor rates for SKA Phases 2 and 3 are catered for with the introduction of 40GigE and 100GigE while allowing SKA Phase 1 systems to co-exist and grow. Ethernet allows for

5. Ethernet as the COTS Interface

Ethernet provides for a common Layer 2 interface across all sensor types as described in the section 4. It caters for individual sensors used in SPF’s, multiple sensor beam-forming aggregation tasks in SAA’s and PAF’s and resultant correlation compute tasks. Expected growth in sensor rates for SKA Phases 2 and 3 are catered for with the introduction of 40GigE and 100GigE while allowing SKA Phase 1 systems to co-exist and grow. Ethernet allows for
the upstream optimization of traffic throughput and flexible growth by integrating individual interface under-subscriptions by utilizing switching aggregation fabrics.

Sensor data received in radio astronomy is aggregated over time and where arrays are used across multiple sensors. Low intermittent loss over a short period from a single sensor although undesired can be tolerated given the loss does not significantly alter the resulting correlated data. Ethernet’s frame drop action when a link or fabric becomes saturated can be minimised if aggregated input streams do not oversubscribe the channelled output streams on the uplinks.

Server interconnections are moving to native support for 10GigE and are becoming available at 40GigE by 2014 and 100GigE by 2020. This trend if realised will enable server technologies to be used for astronomy correlation tasks while minimizing on the physical interface numbers and fibre connections required. Given the number of sensors in the SKA the adoption of 40GigE and 100GigE by 2020 will reduce server numbers, interface counts and power needs. Figure 8 shows the server connection speed and adoption curve up to 2020.

6. WORKED EXAMPLE FOR SKA PHASE 1 TRANSMISSION CAPACITIES

Transmission from SPF sensors is comfortably within existing standards based technologies for local area, short haul and long haul transmission systems. SKA Phase 1 would require three 10GbE interfaces or a single 40GbE interface for each dish. Long haul transmission would require a single pair of fibres given an 80 channel 100G Dense Wave Division Multiplexing (80x100G DWDM) transmission systems are used. Figure 10 outlines the aggregation and switching hierarchy for the SPF capability.

![The defined standard of 40GigE & 100GigE, (IEEE Std 802.3ba-2010) allows for the smooth transition and upgrade path of today’s networks. The ongoing support, performance upgrades, multiple vendor availability for switching hardware, and interface chip sets coupled with downwards pricing trends and the magnitude performance increases provide for a predictable best-fit industry standard for SKA Phase 1 Sensor interconnects and a scalable path towards SKA Phase 2. Accelerated annual port sales forecast vs. the drop in average sales price over the next 4 years show 10GbE to be a cost effective technology to base SKA Phase 1 A-D sensor outputs as the COTS interface of choice. Figure 8](image-url)
Similarly post-beam-formed outputs from PAF sensors can comfortably be transmitted over existing fibre optic systems and standards based interface technologies. Each dish requires 93 x 10GbE interfaces or if aggregated 10 x 100GbE interfaces. Long haul transmission to a central correlation facility could aggregate 8 dishes for each pair of fibre using an 80x100G DWDM transmission system. Thirty pairs of fibre would be required to transport all 250 PAF Dish post beam-formed outputs to an off-site correlation facility. Figure 11 outlines the aggregation and switching hierarchy for the PAF.

**Figure 11: PAF Aggregation & Transmission**

Transmission from each SAA will require 130 x 10GbE interfaces aggregating to 13 x 100GbE to consolidate station traffic. Long haul transmission to a central correlation facility would require a eight pairs of fibres with 80x100G DWDM systems. Figure 12 outlines the aggregation and switching hierarchy for the SAA capability.

**Figure 12: SAA Aggregation & Transmission**

If all correlation capabilities were to be implemented off-site from the core location a total of 40 pairs of fibre using 80x100G DWDM would be required for SKA Phase 1 including an additional pair of fibres for Monitor & Control and Timing.

---

### 7. Conclusions

The SKA poses some advanced and challenging computer networking requirements.

Industry already has standards based multiplexing, switching and transmission systems in-place that will satisfy the SKA raw data communications requirements for Phase 1 of the project today and standards are being ratified to satisfy the requirements for Phases 2 and 3.

In order for the SKA to remain on the data communications growth and cost curves it will need to adopt a framework to output data from as close as possible to the individual sensor in formats adhering to industry standards interfaces and protocols. We have presented aggregation suggestions for SKA Phase 1 that employs the Ethernet protocol as a coherent transmission and data aggregation mechanism across the differing sensor types and sampling rates to their correlator whether they be <1km or 3000km apart. Figure 13 outlines the COTS Industry equipment and capabilities for SKA Phase 1 that is available today and identifies industry standards based interfaces for integration and custom development within the astronomical community.
Intelligence in bandwidth aggregation capabilities coupled with systems growth support is a critical factor for building a scalable SKA. A data communications network based upon Industry Standards with intelligent switching capabilities minimizes the data administration interaction while providing a supported upgrade path towards SKA Phases 2 and 3 as the market adapts higher speed interfaces and greater capacity switching and transmission systems.

The adoption of the Ethernet protocol as the baseline interface between sensor and compute functions satisfies the scientific requirements of the SKA while maximizing on price/performance curves by adopting industry standards and COTS equipment to fulfil the data aggregation and transmission tasks. It provides for close industry involvement via a defined and well-understood communications interface between industry, the astronomy researchers and systems engineering researchers architecting the SKA.

The number of services with up to 3200 100GigE interfaces effectively precludes any circuit based service provision model for even SKA Phase 1. Any service model for the SKA will need to be based upon fibre count rather than circuits. Given even a post-correlation reduction by a factor of 100 with all beam-forming and correlation tasks residing on-site, a pair of fibres would be required for SKA Phase 1 and at least 10 pairs for the SKA.

8. REFERENCES


