D78: Overall Broadband Demonstration

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1. Introduction

This report describes work performed with the goal of enabling an external radio telescope to be connected into the e-MERLIN correlator and correlated against other e-MERLIN antennas. Due to delays experienced in receiving equipment to build the e-MERLIN correlator, which have been beyond the control of Jodrell Bank Observatory, it has not yet been possible to perform a final demonstration of this. The current status, therefore, shall be explained in this report.

2. Data capture and transport

In the current MERLIN system, radio astronomy signals are received at each antenna, mixed with local oscillators to lower the radio frequency (RF) down to an intermediate frequency (IF) and then transmitted over a microwave link to the correlator at Jodrell Bank Observatory (JBO). The signals from each antenna are then processed and digitised within the correlator, and then correlated.

One of the fundamental differences between MERLIN and e-MERLIN is that the radio signals are now digitised at the antenna and transmitted over fibre optic links to the e-MERLIN correlator. The transmission of these signals, however, is not reliant upon standard protocols such as Ethernet or TCP/IP and so not readily transmittable over standard networks. Hence, in order to connect an external antenna into e-MERLIN over regular Wide Are Networks, separate hardware must be employed at the external antenna for capturing and transmitting the data, as well as at the correlator to receive the data stream and input this to the correlator.

To accomplish this task, iBOBs[1] (internet Break out Boards) have been used. These are FPGA based devices, which feature two 10 Gigabit Ethernet capable CX-4 ports, for high-speed network connectivity, as well as 2 Z-DOK connectors which interface directly to the FPGA and can be programmed to behave as required. The iBOBs must be programmed with a firmware to control their behaviour, and variations have been written at JBO and Metsähovi Radio Observatory.

For data capture and sampling, a dual 1 GHz analog to digital converter[2] (ADC) is plugged into one of the Z-DOK connectors on the iBOB. MRO were tasked to produce the firmware for capturing data from the ADC, and they also implemented a method of transmitting the sampled data over the CX-4 connectors in order to test and analyse the sampled data on a standard PC.

iBOB related work at JBO was concentrated on transmission and reception of the sampled data using the VDIF format, and feeding the output of the iBOB to the e-MERLIN correlator Station Boards.

3. Network Connectivity

The transmission of 4 Gbit/s of data over shared academic networks is possible to some extent, but has the potential of impacting other users, especially since the data stream will be UDP based and therefore not regulate itself if faced with congestion. Onsala already had a pair of 1 Gbit/s links to the academic Internet, one for general observatory traffic and the other was reserved for e-VLBI use. In order to support e-MERLIN and higher bandwidth e-VLBI, this link was upgraded to 10 Gbit/s in November 2007. The existing Coarse Wavelength Division Multiplexing (CWDM) equipment was replaced by Dense Wavelength Division Multiplexing (DWDM) equipment, which allowed both the original 2x 1 GE links to continue operating as before whilst adding a 10 GE link over the same fibre pair.

At the observatory, the 10 GE link is presented as a long reach fibre optic link and connects to an HP 6400cl 6-port CX-4 switch. The switch provides 6x 10 gigabit CX-4 ports at the front, and a pair of X2 modular ports at the rear, one of which is populated with a 10 GE Long-Reach optic. The link runs as a dedicated lightpath between the observatory and a NORDUnet point of presence (POP) located in Stockholm, where it terminates in a Juniper MX480 router (SUNET project router in *Figure 1*). From this router, a routed 10 gigabit connection is available to the IP network, as well as a 10 gigabit layer 2 connection to the Alcatel Transport Service Switch (TSS) platform implemented by NORDUnet. From the TSS, layer 2 connections can be made to several destinations; currently 4 Gbit/s is allocated within the TSS to Jodrell Bank, 1.5 Gbit/s to JIVE, and 4.5 Gbit/s to LOFAR.

Data streams are directed towards a particular destination through a combination of Virtual Local Area Network (VLAN) tags (ID numbers) and IP addressing. To reach the routed IP network, or JIVE via the TSS, devices based at the observatory are assigned an IP address from a routable /29 subnet allocated by SUNET. Ethernet frames from these devices are then given a VLAN tag at the HP switch, which informs the SUNET router that these frames should be routed to the IP network. At the same time, the SUNET router examines the destination IP address, and if this is contained within the JIVE IP address space, then the frames are instead tagged with a new VLAN ID and switched into the TSS platform and onto JIVE. In this respect, the link to JIVE is a routed connection over dedicated layer 2 links. Data streams intended for any other destination within the TSS are tagged with the relevant VLAN ID at the HP switch and transparently switched into the TSS by the SUNET router.

To communicate between Onsala and Metsähovi, data is routed over the shared Nordic academic IP network infrastructure, as seen in *Figure 1*, at rates of up to 10 Gbit/s, dependent upon background traffic which is typically below 3 Gbit/s. For occasional testing purposes, the network operators have agreed that we can transmit high-bandwidth UDP flows over the shared network, provided that we notify them in advance.

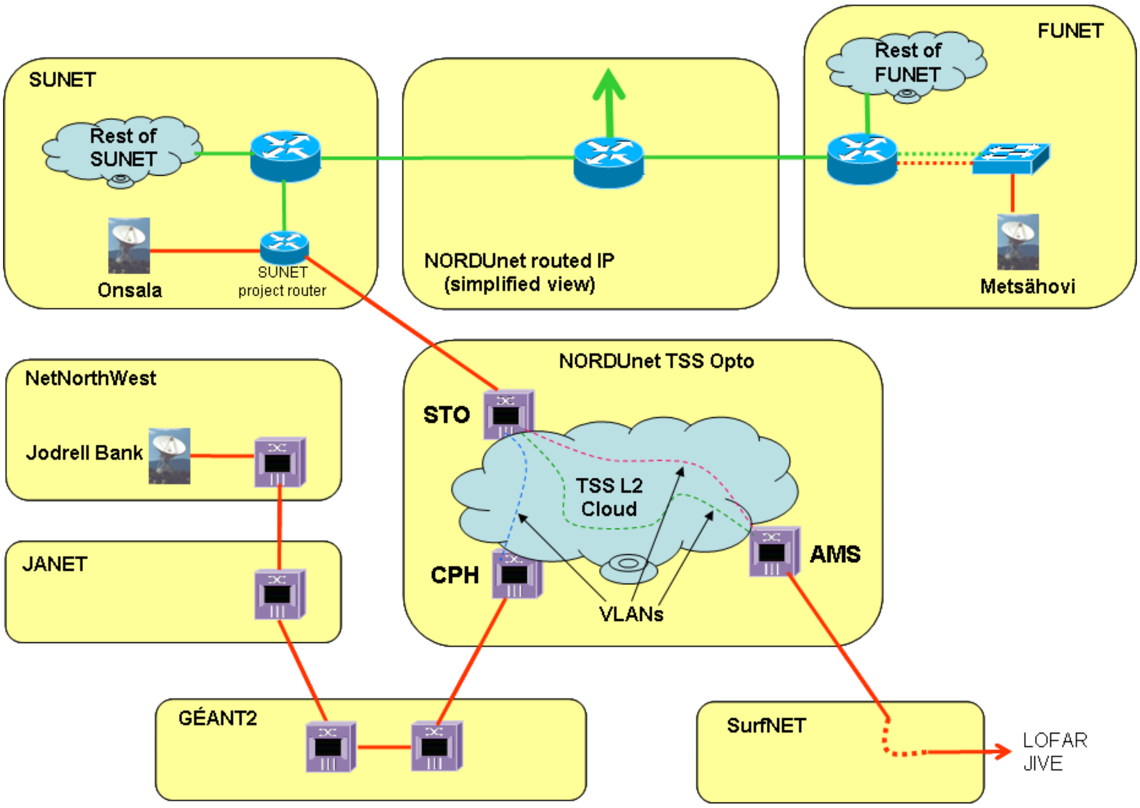

Figure 1: *Network connectivity between Onsala and Metsähovi, LOFAR, JIVE, and Jodrell Bank.*

4. Tests conducted thus far

Whilst fringes between Onsala and another e-MERLIN antenna have not yet been obtained due to delays with the new e-MERLIN correlator, the individual components which will accomplish this goal have been tested and shown to be working as expected.

4.1 Data acquisition

Both OSO and MRO have conducted tests using the acquisition firmware supplied by MRO. These have included sampling a signal generator connected to the ADC input, as well as sampling broadband feeds from a radio telescope. MRO produced an accompanying PC application which captures a UDP stream sent by an iBOB and records this to disk, allowing the signals to be processed with standard software tools. The iBOB transmits datagrams containing 8 bit time-samples, and typically these are Fourier transformed then summed to produce an auto-correlation.

An experiment was conducted at the beginning of November 2008, where data were captured from the 20m Onsala telescope on an iBOB located at Onsala, then transmitted over the shared Nordic academic Internet, and recorded in real-time on a PC based at Metsähovi. The radio maser W3 was observed at a frequency of 22 GHz, and the sampled data were successfully transmitted and received at a rate of 4 Gbit/s over a period of 5 minutes. For noise calibration purposes, a further 5 minutes were recorded whilst the telescope was not pointing at a radio source. Processing of the two data sets was performed at Onsala, and the results can be seen in *Figure 2*.

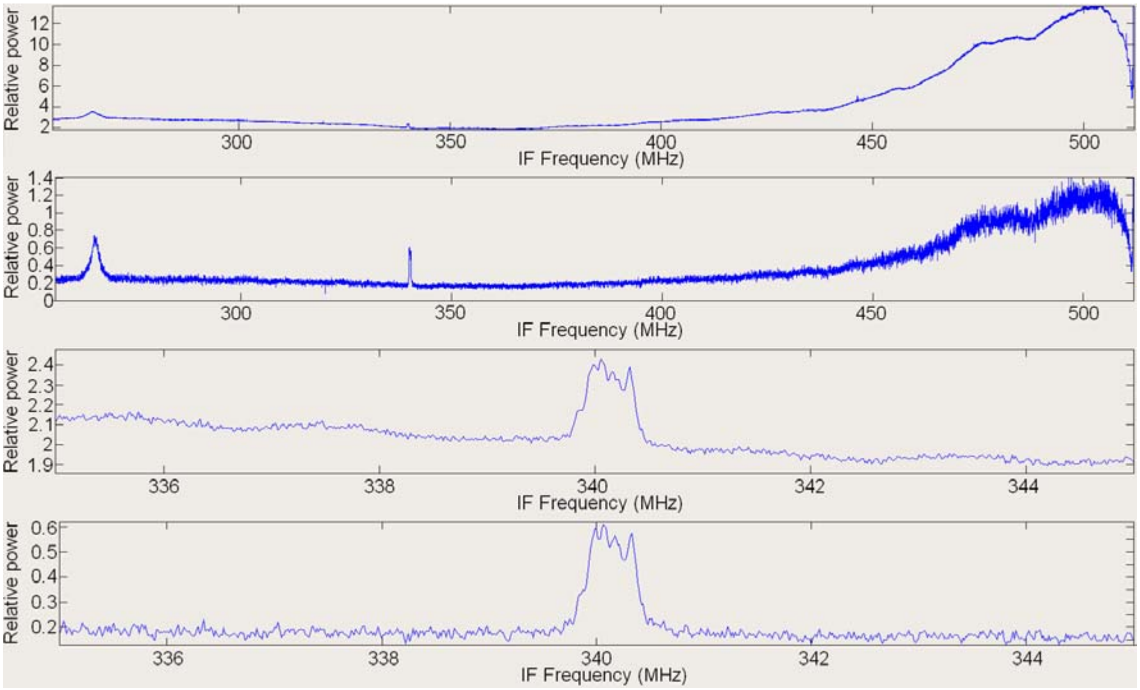

Figure 2: *Water spectra of W3 as captured by an iBOB, 13kHz channel bandwidth, 30s integration. First plot shows on-source data over IF frequency range 256-512 MHz, second plot shows off-source data subtracted from on-source; third and fourth plots are as first and second but over IF frequency range 335-345 MHz.*

This clearly demonstrates the data sampling and acquisition capabilities of the iBOB, not only as a digital receiver for e-MERLIN, but also as a very flexible software spectrometer; once the raw data is captured, the user can then specify a channel bandwidth when performing the autocorrelation, giving spectral resolutions down to the order of hundreds of Hz.

4.2 iBOB network performance

As mentioned previously, JBO have been working on network code for the iBOB and the interface to e-MERLIN. Expanding on the network code for the purpose of e-MERLIN, the iBOB firmware has been created such that the iBOB will also function as a network test device. Not only does this help to demonstrate the stability of the iBOB in sending data at a fixed rate, as generally required in VLBI, but also creates a very useful tool which can be deployed at sites for monitoring network performance and diagnosing problems. Indeed, the iBOBs were used in this way to diagnose a packet loss problem which was being experienced over the 4 Gbit/s link.

Figures 3-5 illustrate the stability of the iBOB when transmitting packets to the network, both at a macro level over 20 hours in *Figure 3*, and at the individual packet level in *Figures 4 & 5*. By comparing *Figures 4 & 5*, it can be seen that two independent runs exhibit extremely similar characteristics. The quantity displayed is the difference in arrival times between each pair of packets when received by the remote iBOB. The target packet spacing was 16 μs, and this agrees with the modal packet spacings on reception, as displayed in the figures. Since the packets were being transmitted over a network, and not simply from an iBOB directly connected to a second iBOB, some of the features present in the figures will have been caused by devices in the network.

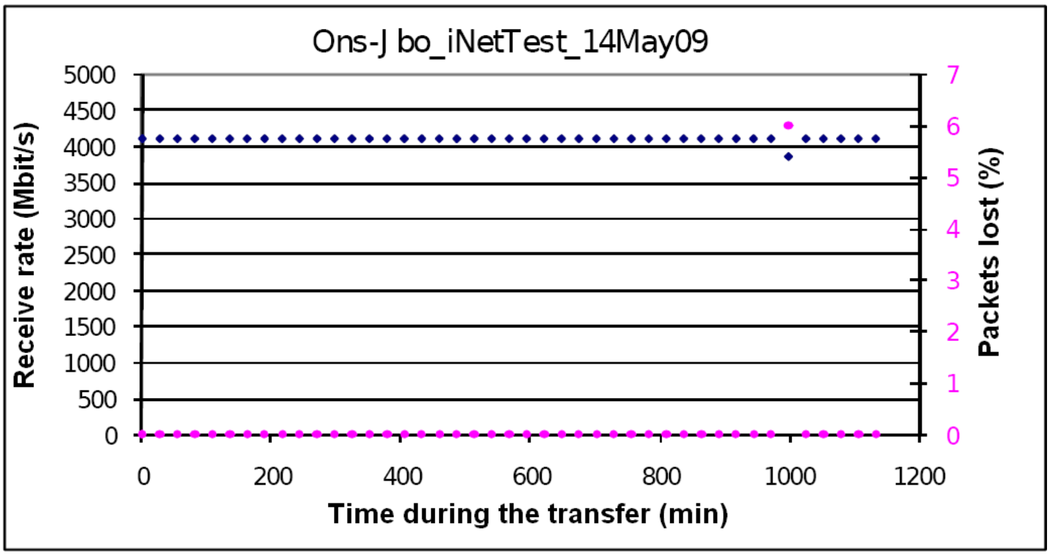

Figure 3: Continuous *iBOB to iBOB bandwidth tests OSO – JBO. Each point represents an individual test, transmitting 10^8 packets of 8192 bytes at a spacing of 16 μs. (Richard Hughes-Jones, DANTE)*

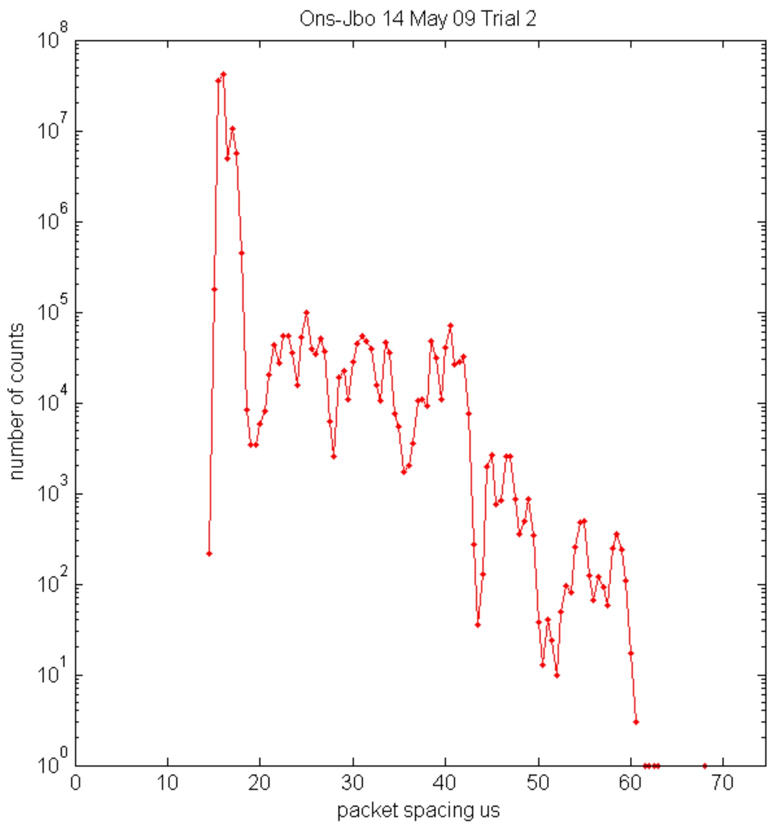

Figure 4: *Time between arrival of subsequent packets in run 2 of Figure 3. (Richard Hughes-Jones, DANTE)*

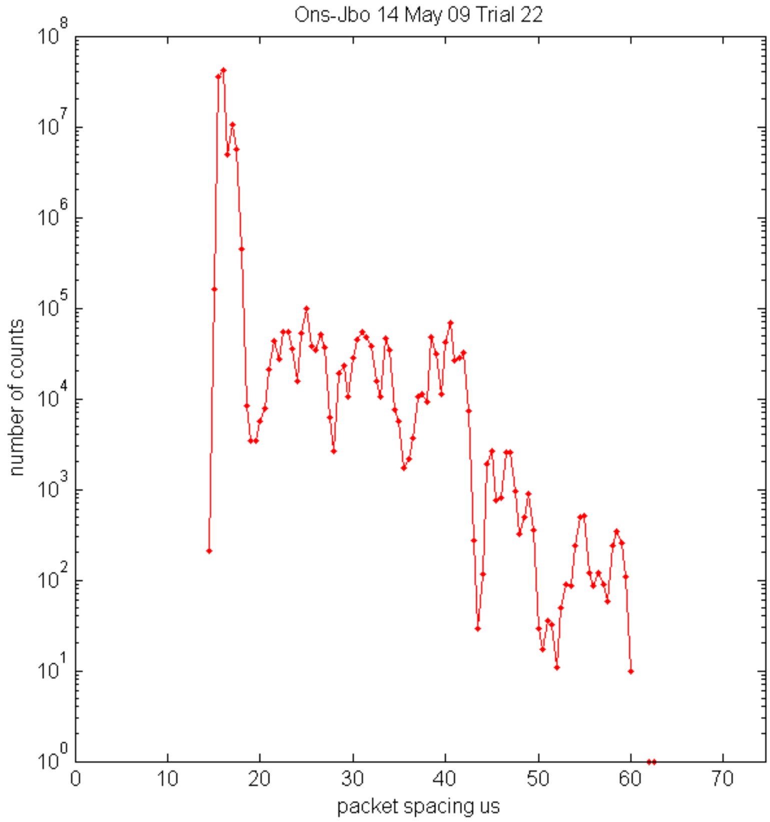

Figure 5: *Time between arrival of subsequent packets in run 22 of Figure 3. (Richard Hughes-Jones, DANTE)*

4.3 iBOB input to the e-MERLIN correlator

Signals from regular e-MERLIN antennas pass through Station Boards (SBs) before being passed to Baseline Boards for cross-correlation. The SBs serve to de-format the incoming data stream, and to split the wideband data into several sub-bands through the use of filter banks. External antenna data from the iBOB also passes through a SB in a similar fashion.

For diagnostic purposes, it is possible to examine the state counts at the input of the SB, and also in the filter banks. The state counts give an count of the number of data points in the signal which were detected at a certain voltage level. *Figure 6* shows a histogram of the state counts when the input data was an 88 MHz sinusoid, sampled by an iBOB at OSO, and transmitted to an iBOB at JBO, whence it was fed into the SB. For a regular sinusoid, you should expect to see a 'U' shaped histogram, with the outer peaks represent time spent in the highest and lowest states. As the input signal is strengthened, more counts would be detected at the maxima since the wave will be clipping and approaching a square wave. Likewise if the signal is attenuated, the outer counts would move towards the centre. This effect has been experimented on, and the results can be seen in *Figure 7*.

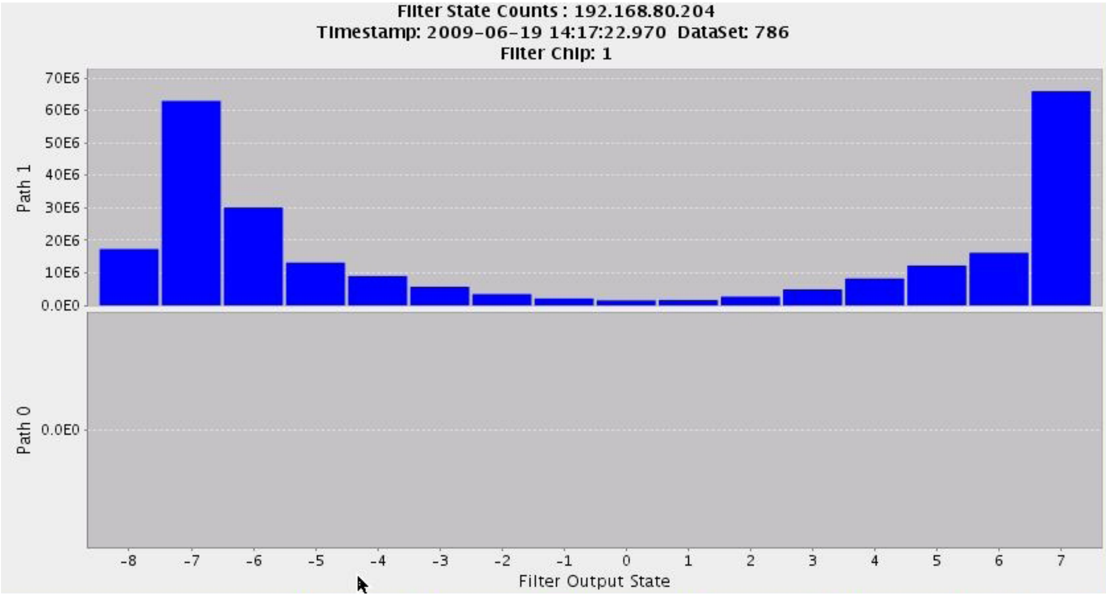

Figure 6: *State count histogram from e-MERLIN Station Board filter chip. Input signal was 88 MHz sinusoid generated at Onsala and transmitted via iBOBs to Jodrell. (Jonathan Hargreaves, Jodrell Bank)*

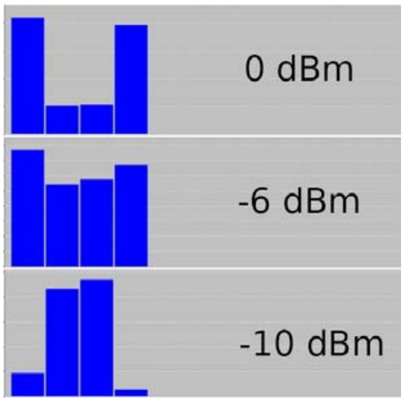

Figure 7: *State count histograms from e-MERLIN Station Board input chip, demonstrating effect of different amplitude sinusoids on state counts. (Jonathan Hargreaves, Jodrell Bank)*

5. Conclusions

The results presented within this report show that the majority of work required for demonstrating fringes between OSO and an e-MERLIN antenna has been successfully achieved. Data can be sampled at OSO, transmitted over the network, and fed into the e-MERLIN correlator, leaving only the final correlation steps to be accomplished in order to produce OSO – e-MERLIN fringes. This has not yet been possible due to the delayed delivery of the e-MERLIN correlator, and the main priority from an e-MERLIN point of view so far has been to achieve fringes between native e-MERLIN antennas first. These have very recently been obtained, thus paving the way for fringes to Onsala, and in this respect work is still on going.

[1] http://casper.berkeley.edu/wiki/IBOB viewed August 2009
[2] http://casper.berkeley.edu/wiki/ADC2x1000-8 viewed August 2009