A MULTI-TERABIT OPTICAL FIBRE NETWORK FOR A LOFAR TELESCOPE

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ABSTRACT

In the astronomy world, there is a need for high-performance radio telescopes operating at low frequencies. Such a telescope can be realized by a large network of small dipole antennas spread over an area of about 360 square kilometers. This antenna configuration requires a multi-terabit optical network to transport and collect the massive amounts of data picked-up from the sky. Within the Retina project, we have developed an architecture for such a multi-terabit optical network. In addition, new 160 Gbit/s line rate technology has been developed that can be used in such a network.

THE LOFAR ANTENNA SYSTEM

For observing events far away in the universe, extremely sensitive radio telescopes with very high resolution are needed. Such a high-performance telescope can be realized by deploying large numbers of antenna elements, spread out over a wide area. The innovative LOFAR (Low Frequency Array) antenna system [1] uses 13104 separate broadband dipole antennas, each of the order of a meter in size, and positioned in an area with a diameter of approximately 350 km (see Fig. 1). The radio signals captured by the individual antennas are digitized and transported to a central signal processor. Each antenna is omni-directional. By adjusting the delays of the digital signals from several antennas, and correlating them with the appropriate weight factors in the processor, a well-defined beam for observing the universe in a certain direction in real time can be formed. Since this combination is done digitally, it is well possible to copy the signals from each antenna and combine them also with a different set of weights. This way several independent station beams can be formed. By combining stations in the central processor, the directivity within each beam is further increased.

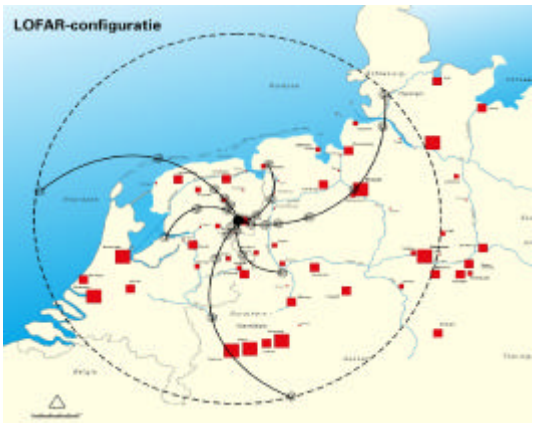

Fig. 1. LOFAR telescope positioned in The Netherlands

Fig. 2. Artist impression of a LOFAR station

Via the Internet, multiple users can operate the LOFAR system at the same time. Choosing different sets of delay times and weight factors enables to create multiple beams for simultaneous observations. Of specific interest is the observation of very remote hydrogen-containing objects, which show spectral absorption lines in the 10 to 240 MHz range. Digitizing these signals yields a bit stream of 2 Gbit/s per dual-polarisation dipole antenna.

The antennas are grouped in 168 stations of 78 antennas each (see Fig. 2). The stations are arranged in a central area and along three short and three long curved arms, which converge in the central area. The central area has a diameter of 1.2 kilometers and will contain 42 stations. Each short arm has a length of 45 kilometers and contains 14 stations. Each long arm has a length of 235 kilometers and contains 28 stations. This adds up tot a total of 168 stations. Each station produces a 160 Gbit/s data stream, and the aggregate data flow to the central processor is some 26 Tbit/s.

THE RETINA OPTICAL FIBRE NETWORK

The RETINA (Remote Elements Telescope Intelligent Network Architecture) project is investigating an optical fibre network to transport the huge data streams to the central processor. Within a station, optical Gigabit Ethernet (GbE) network technology will be used to combine the 2Gbit/s data streams of the antennas in the station. This ends up to an interface towards the core transport network that consists of 16 ports of 10GbE each. At the central processor side, the interface to the core transport network is mirrored for each station. Thus, on the central processor side, the interface also consists of 16 ports of 10GbE per station. The optical core transport network has to make the leap to connect the interface of each station to the interface at the central processor.

In the optical networking arena there are three main techniques to multiplex data streams from different sources [2]. The first and most simple one is called Space Division Multiplexing (SDM). With SDM, each data stream is put onto a separate fiber to be transported towards the destination. In case of our network, this technique can for instance be used to transport each of the 16 10Gbit/s streams of a station towards the central processor on a separate fiber. In that case, 16 fibers per station are needed.

The second multiplexing technique is called Wavelength Division Multiplexing (WDM). With WDM, several data streams are multiplexed onto a single fiber, where each data stream is transported on a separate wavelength or color. A passive optical WDM multiplexer is used to multiplex the wavelengths onto a single fiber. In case of our network, this technique can for instance be used to multiplex the 16 10Gbit/s streams of a station onto a single fiber. In that case, 1 WDM multiplexer and 1 fiber per station are needed in which 16 colors are transported.

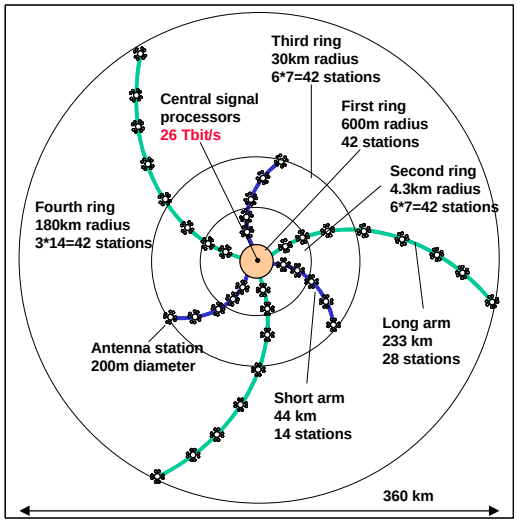

Fig. 3. Distribution of stations in the network

The third multiplexing technique is called Time Division Multiplexing (TDM). With TDM, several data streams are multiplexed in time onto a single fiber using a single wavelength. The data streams are thus interleaved using a TDM multiplexer resulting in a larger bandwidth per wavelength. The TDM multiplexer translates the data streams from an

optical to an electrical format, multiplexes the streams and converts the resulting electrical data stream back to an optical format. Electrical data streams are at the moment technically possible up to a data rate of 40Gbit/s. In case of our network, this technique can for instance be used to multiplex 4 10Gbit/s streams of a station into one 40Gbit/s stream that is put onto a single fiber. In that case, 4 TDM multiplexers and four fibers per station are needed.

We have investigated the network architecture options for the central area, the short arms and the long arms. In this network architecture, a combination of the multiplexing techniques is used. The preliminary results of this study are presented below.

Central Area Network Architecture

In the central area, fibre lengths are short (less than 1 km), and point-to-point links from smaller groups of antennas to the central processor are foreseen, operating in the 1300 nm fiber transmission window. Given the very short transmission distance, very simple directly modulated DFB laser diodes developed to support 10GbE (representing the 1300 nm arena par excellence) can be applied. No amplification of the signal is needed along the fiber path. Recently, direct laser diode modulation up to 20 Gbit/s at 1300 nm has been reported, providing an even more cost-effective approach [3]. At the moment, the central area network architecture envisioned consists of 16 10GbE point-to-point links (at 1300 nm) per station to the central processor. This is thus a complete SDM solution that consists only of fiber in the core transport network. It is currently being investigated whether this is the most cost-effective solution. An alternative might be to use a WDM solution per station. This saves fiber, but increases the cost with two WDM multiplexers, one at the station and one at the central processor.

Short Arm Network Architecture

Each of the short arms of 45 km contains 14 antenna stations, and adding signals along this route amounts to 2.24 Tbit/s upstream traffic. Due to the shorter fibre lengths, operation in the 1300 nm window with its added advantage of low dispersion is envisaged. However, the low dispersion in standard single-mode fibre may generate sizeable non-linear effects such as Four Wave Mixing (FWM), asking for a controlled amount of non-zero local dispersion [4]. By deploying the 1300 nm window for the LOFAR applications, the 1550 nm window remains available for regular telecommunication services. This offers advantages to network operators, who thus may share (a part of) their network to host the LOFAR infrastructure. Special measures (such as 1300/1550 nm coarse WDM de-multiplexers) are required to process the two wavelength windows at critical network nodes. At the moment, long-range 10GbE lasers have a reach of about 60 kilometers without amplification. All the stations on the short arm are within a distance of 45 kilometers of the central processor. Thus, 10GbE point-to-point links in the 1300 nm window can also be used for all the stations on the short arms. This is a similar SDM solution as the one used in the central area. The WDM alternative to multiplex the 16 10GbE data streams onto a single fiber is also an attractive solution. In that case, the fiber distance becomes large enough to make the cost of 2 WDM multiplexers less then the cost of 16 fibers. The exact balance in cost between the two solutions is currently investigated.

Long Arm Network Architecture

Each of the long arms contains 28 stations. The first 14 stations on each long arm have the same distance to the central processor as the 14 stations on the short arm. Consequently, the same SDM or WDM solution can be used there. For the outer 14 stations on the long arm, a separate solution is needed. At the moment, we have chosen for the 1550nm window, because of the relatively low loss. Thus, larger distances can be reached with a smaller number of amplifiers along the fiber path. The entire SDM solution for these stations (16 fibers per station) is not cost-effective due to the long distance to the central processor. Thus, WDM and/or TDM techniques have to be used. For instance, a WDM multiplexer for the 16 10GbE data streams per station can be used to put 160Gbit/s onto a single fiber towards the central processor. Another solution is to use a TDM multiplexer for 4x10GbE data stream (to reach 40Gbit/s) and after that a WDM multiplexer for 4x40Gbit/s to put 160Gbit/s onto a single fiber towards the central processor. In addition, there are some ten other solutions that are currently technically possible. Each of these solutions is currently being investigated to see which one is most cost-effective.

160GBIT/S OTDM TECHNOLOGY

The SDM, WDM and TDM solutions discussed in the previous sections are all based on optical equipment that is currently on the market. Another technology that is currently in a research phase is 160Gbit/s Optical TDM (OTDM) [5]. With OTDM, several data streams are multiplexed in the optical domain onto a single wavelength. This needs to be done in the optical domain, because it s not yet possible to do this in the electrical domain at these high speeds. No electrical clocks are available yet at 160Gbit/s. Within the RETINA project, we are investigating this technology and apply it in the LOFAR network architecture.

Two architectural options are considered: one using a combination of dense WDM (DWDM) and OTDM techniques, and a second one deploying SDM in combination with OTDM.

In the DWDM/OTDM network architecture option, each of the network arms encompasses a number of stations, and a separate wavelength channel in the 1500 nm window is assigned to each station. Adding signals along the way towards the central processor, the aggregate upstream traffic amounts to several Tbit/s. Multi-wavelength optical amplifiers are compensating the network splitting and fibre link losses. To enable dynamic remote shaping and pointing of the observation beams, the assignment of channels to the antenna stations can be changed by using flexible wavelength add-drop multiplexers as well as flexible OTDM multiplexers. Thus it is also possible to operate the system at a decreased data rate such as 16 Gbit/s per station, at the expense of a decreased system performance.

Within a station, the signals of the 16 10GbE data streams are firstly multiplexed into 4 streams of 40 Gbit/s each, and then by OTDM combined into a 160 Gbit/s stream per station. Concepts for the OTDM and de-multiplexing functions are investigated. In particular, the options for high-speed narrow-pulse sources, for fast optical gates (e.g. electro-absorption modulators) for optical multiplexing and de-multiplexing, and for stable clock extraction as required for synchronisation of the de-multiplexing. Also an analysis is made of the transmission performance of a multi-wavelength signal carrying multiple 160 Gbit/s data streams, in view of required fibre characteristics (dispersion, non-linear effects), source properties, optical amplifier characteristics, etc. OTDM add/drop functions will be studied for injecting the (on cluster level aggregated) antenna data signals into the 160 Gbit/s main stream. The investigations will encompass OTDM techniques in the 1300 nm wavelength region for the central area and for the short arms, as well as OTDM techniques in the 1500 nm region for the long arms.

Another architectural option is to deploy SDM in combination with OTDM. In that case each station is connected with a separate fibre to the central processor. At the central signal processor site, an optical cross-connect can flexibly assign transceivers to one or more stations. The DWDM/OTDM solution requires less fibers and optical amplifiers than the SDM/OTDM one, and thus offers better opportunities for merging with other services in the same cable sheet.

CONCLUSION

We have studied possible architectures for a multi-terabit network of antenna telescopes. In these architectures, 10 and 40 Gbit/s optical commercial networking equipment can be used. Even higher speeds, like 160 Gbit/s line rate, can be foreseen in such networks in the next 3 to 5 years. Based on the cost-effectiveness of the different possible network architectures a specific commercial architecture will be selected for the LOFAR network.

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