Application of Ultrahigh-speed Network to Advanced Science

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Abstract

A joint research project on real-time very long baseline interferometry (VLBI) called GALAXY is being conducted by NTT Laboratories, the Communications Research Laboratory, the National Astronomical Observatory, Yamaguchi University, and the Institute of Space and Aeronautical Science to explore the effectiveness of ultrahigh-speed communications technologies when applied to advanced scientific research. VLBI is a very precise measurement tool for radio astronomy and earth science based on cross-correlating observed radio signals received at a number of antennas located far apart. Using an ultrahigh-speed network allows us to raise the bandwidth of the radio signals used for the cross-correlation, so the performance of the observation system can be greatly improved. This paper outlines the project and presents recent developments in our research activities focusing on new networking technologies utilizing the Internet protocol.

1. Introduction

In recent years, the application of ultrahigh-speed networks to advanced scientific research has started to attract a great deal of attention with the rapid improvement of research and education (R&E) networks funded by governments and parts of the private sector. Typical applications being tried include ones in the fields of high-energy physics, astronomy, genetic engineering, and distributed computing. Among them, the leader is real-time very long baseline interferometry (VLBI), which creates a large-scale virtual radio telescope and is a very precise system for measuring the earth's rotation parameters using multiple distantly located antennas. VLBI itself is an established technology developed in 1960s and many scientific discoveries have been made in astronomy and geodesy using it [1], [2]. The key point of our research project called GALAXY is to remove the performance bottleneck of the conventional VLBI scheme by using an ultrahigh-speed communications network to carry observed data, which previously had to be physically transported on magnetic tapes. The name "real-time VLBI" comes from the fact that the data streams are processed online during an observation. Our colleagues outside Japan call this scheme "e-VLBI" or "VLBI-Grid", but the concept is the same.

NTT Laboratories has been conducting a joint research project on real-time VLBI since 1995 with national research institutes including the Communications Research Laboratory (CRL), the National Astronomical Observatory of Japan (NAOJ), the Institute of Space and Astronautical Science (ISAS), Yamaguchi University, and Gifu University. This was the first attempt in the world to use a high-speed digital communications network for a VLBI observation system. NTT's objectives for the project are two-fold. One is to establish technologies for very-high-speed communications (gigabit-per-second class) in preparation for commercial services in the future. The second is to explore and prove the effectiveness of those technologies in advanced scientific areas, which are the first actual applications utilizing the capabilities of ultrahigh-speed communications technologies.

To investigate the problems related to ultrahigh-speed communications and evaluate developed schemes and technologies, we constructed a dedicated experimental network using asynchronous transfer mode (ATM) technology in 1996. ATM was devel-

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oped as the transmission technology for broadband communication services at the time and the technology provided us with a very reliable and flexible means to carry a vast amount of data on our experimental network. While it worked very well on our closed experimental system, we found some drawbacks to using ATM, notably a high cost for high reliability but limited connectivity to other antennas and research institutes.

To solve these problems, we started to use the Internet protocol (IP) to lower the transmission costs and obtain more flexibility. Using IP technology raises many technical issues. Many of the problems are related to the characteristics of the Internet architecture itself, which does not have a mechanism for assuring the quality of service (QoS). On the brighter side, this approach has proved suitable for a new data processing architecture using many inexpensive CPUs. This might open the way to building a new distributed very-high-speed data processing architecture that makes the conventional centralized cross-correlator architecture using a special purpose supercomputer obsolete. Thus, our interest in the GALAXY project has shifted from straightforward ultrahigh-speed data transmission to the very complicated network computing architecture that will fully utilize the flexibility of IP technologies.

This paper outlines the GALAXY project and presents recent developments in our research activities, focusing on new networking IP technologies. After briefly reviewing the history of the project and the basic concept of realtime VLBI, I address the technical issues related to networking and the parallel IP VLBI data transmission scheme that we have developed. Finally, I mention our future research plans.

2. GALAXY project

2.1 NTT's very-high-speed network experiment and GALAXY

In 1995, just after the start of NTT's "Multimedia Service Experiment" using the nationwide 155-Mbit/s experimental network [3], NTT Laboratories started a joint research project on ultrahigh-speed communications with many research organizations using a large-scale network testbed having the maximum speed of 2.4 Gbit/s. Its aim was to pursue the use of an ultrahigh-speed network in scientific applications that could not be tested on the 155-Mbit/s network.

The application areas covered a wide range, including very-high-speed parallel processing and precise clock synchronization, and each application was tried out using the dedicated experimental network for three years. Among many applications tried in the project, real-time VLBI in particular proved to benefit greatly from the use of ultrahigh-performance communications because real-time data transmission using an ultrahigh-speed communications network eliminated the transmission bottleneck in the conventional VLBI system. The performance of the observation system could be significantly improved in terms of sensitivity.

The Key Stone Project (KSP) led by CRL and the OLIVE project led by NAOJ and ISAS, which were both conducted during this phase-1 project, definitely proved the effectiveness of real-time VLBI. Therefore, it was judged that this approach should be pursued even after the phase-1 project ended. We also found many more significant potential applications that would only be possible with real-time VLBI technology. Thus, the phase-2 project, called GALAXY, started in 1998 combining KSP and OLIVE and focusing on advances in real-time VLBI technology. An extensive list of research topics related to real-time VLBI technology is being investigated, together with scientific observations using our experimental observation system [4], [5].

2.2 Conventional VLBI and real-time VLBI

VLBI cross-correlates data streams from multiple radio telescopes targeting the same radio source in the universe. Although the main component of each data stream received at an antenna site is white noise, by cross-correlating the streams received at different antennas, we can measure minute differences between the signal arrival times very precisely. Because the radio signals from distant radio sources can be regarded as plane waves, we can also calculate the distance between the antennas from the time differences. On the other hand, the image of the radio source can be reconstructed by processing the luminous distribution of the radio source obtained from many antennas. VLBI can obtain the same angular resolution as a radio telescope having a reflector whose diameter is equal to the distance between the antennas used for the VLBI.

From the viewpoint of signal processing, the sensitivity of the observation system is determined by the bandwidth of the signal streams to be cross correlated. With the conventional tape-based VLBI system, the amount of observation data was restricted by the physical limitations of its recordable data rates and the storage capacity of the data recorder used for storing observed radio signals at each antenna site. This limits the performance of the total observation system, making it impossible to construct a very sensitive virtual radio telescope with very long baselines (with very high angular resolution).

With the real-time VLBI system directly connecting antennas and data processing units via a communications network, however, this restriction can be removed and more data can be easily utilized for the analyses. This means that the performances of receiver systems (antennas, receivers, and samplers, etc.) and processing units (cross correlators) can be fully utilized. In addition, real-time cross correlation during the observation allows the scientists to check the status and condition of their observation on the spot, eliminating operating errors that often occur with experiments involving many personnel participating at distant sites. Consequently, real-time VLBI has great advantages over the conventional tape-based system in both system performance and observation efficiency. Figure 1 shows the configuration of our experimental system in the phase-2 project.

2.3 Applications of real-time VLBI

Throughout the project, geodesy and radio astronomy have been the main applications of real-time VLBI technology. Last year, however, we started using it to determine the orbit of artificial satellites.

(1) Geodesy

This is a joint trial with CRL to implement a high-precision crustal deformation measurement system using real-time VLBI. CRL has constructed four dedicated antennas in the Kanto area (greater metropolitan Tokyo) for this project called KSP (Key Stone Project). Connecting these antennas with a central cross correlator located in CRL Koganei, Tokyo, enables measurements with very high resolution. The net data rate from each antenna is 256 Mbit/s, making the total rate 1 Gbit/s, and the signals are routed to CRL Koganei via NTT Musashino R&D Center and processed in real time with a hardware cross correlator. This observation system measured the deformation in the Kanto area with millimeter precision in almost real time [6].

From 1996 until the end of 2001, regular measurements (every other day) were conducted using the KSP network and the large amount of observed data has been publicly offered to the earth science community through the CRL web site. In 2001, a major deformation due to sudden volcanic activity in the Izu Islands was clearly observed with this system (Fig. 2).

(2) Radio astronomy

This is a joint effort with NAOJ, CRL, and ISAS

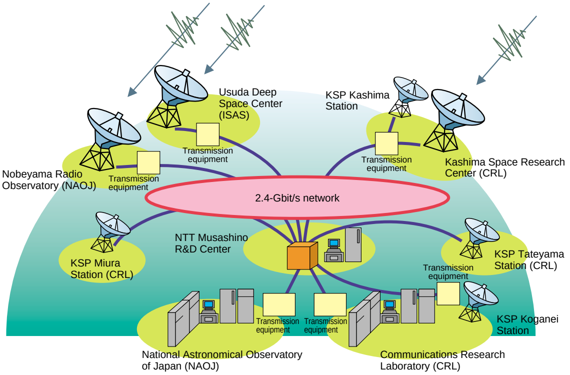

Fig. 1. GALAXY network configuration.

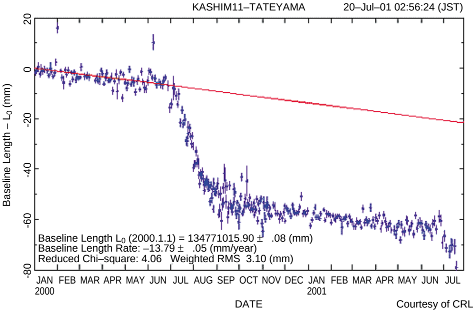

Fig. 2. Site motion monitoring with real-time VLBI.

to implement the world's largest virtual radio telescope having ultrahigh resolution and sensitivity by combining conventional VLBI technology and a Gbit/s-class communications network. The synthesized virtual telescope effectively has the same angular resolution as a telescope with a diameter equal to the distance between the remote antennas, which in the case of the Kashima-Usuda baseline is 208 km [7].

The on-site processing and observation allowed us to conduct very flexible and efficient VLBI observations by constantly checking the obtained data while tracking the target radio source. This is only possible with real-time VLBI technology. We can also use a number of terrestrial antennas together with a space radio telescope using our network. The first fringe (cross correlation) was detected in 1997 between signals received by a terrestrial antenna (Usuda 64 m) and a satellite antenna (HALCA). Real-time correlation was successfully performed among large terrestrial antennas (Usuda 64 m, Nobeyama 45 m, and Kashima 34 m) in 1998. A variation in signal strength of a bursty radio source was successfully observed in a real-time VLBI observation session in 1999 using the Usuda and Kashima antennas.

(3) Space navigation

This is a new application area of VLBI mainly pursued by our colleagues at CRL Kashima Research Center. To control the orbits of artificial satellites, it is necessary to measure orbits very precisely with reference to the solar inertial system. VLBI offers a unique solution to this problem by using a quasar as a reference to the artificial flying objects. Last year, the team led by ISAS and CRL started to apply this scheme to determine the location of the Nozomi Mars probe.

3. Networking issues

3.1 Data transmission technologies for real-time VLBI

The requirements for the transmission technologies for real-time VLBI differ greatly depending on the style of the observation and the required bandwidth. Figure 3 explains suitable technologies for each case.

In the phase-1 project, we built a dedicated experimental network for real-time VLBI and used ATM technology to carry the data. ATM technology has a rigorous bandwidth management capability providing the very reliable data transmission required for critical applications. The relatively high cost can be justified for a high network usage case such as KSP where regular observations were conducted. In the medium to lower network usage cases, however, the use of dedicated bandwidth is not economical. To make the real-time VLBI experiment more affordable and widespread, IP technologies must be used effectively, because the R&E networks around the world are rapidly increasing their capacities and those networks are accessible from major public research organizations around the world at a low cost.

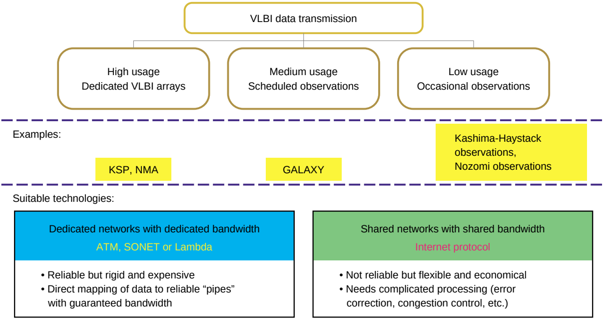

Fig. 3. Data transmission technologies for real-time VLBI.

Therefore, in the phase-2 project we started to explore the use of IP technologies extensively within our experimental network along with ATM taking into account the collaboration with R&E networks around the world. Using IP for transferring very-high-speed data involves many challenging issues. With IP networks, "best effort" is the norm, so we must take measures to assure that the data streams are transmitted to the other end reliably without any degradation of the total throughput. From this viewpoint, we developed a very-high-speed VLBI data transfer system using multiple IP streams, as described in section 3.2.

3.2 Configuration of experimental network

Figure 4 shows the physical configuration of our experimental network with the R&E networks with which we are collaborating. Last year, the GALAXY network was integrated with GEMnet, which is another NTT research network. At the moment, we are upgrading links among NTT research centers with the latest wavelength division multiplexing technologies to augment the capacity of GALAXY/GEMnet. The previous paper in this issue [8] describes the concept and future plans of this new experimental network, which will be the unified high-performance networking testbed of NTT Laboratories.

Connectivity with other research organizations has been greatly improved by interconnecting with other R&E networks. The connection to Super SINET (Science Information Network) operated by the National Institute of Informatics (NII) has greatly improved the connectivity with domestic research organizations, especially national universities. We have a direct link to Super SINET at 600 Mbit/s as well as 2.4-Gbit/s SDH links. Figure 5 shows the configuration of the 4-Gbit/s observation experiment in collaboration with Super SINET. We also have a direct link to Abilene, which is the backbone network of the Internet2 project in the United States. The collaboration with Internet2 provides us with connections to research organizations in the US as well as in other parts of the world via their international transit service (ITS).

We are continually upgrading our experimental network to adapt to our new requirements. One is to deploy more high-performance IP equipment to promote research on "Internet VLBI" and another is to use the latest photonic devices and transmission equipment developed by our laboratories in our network. A high-capacity data storage and video conferencing system supporting the remote distributed experiment have also been deployed.

3.3 Video conferencing system

In the distributed working environment including real-time VLBI, human communication among the scientists working at distant sites plays an important role. When we conduct an observation using the real-time VLBI system, more than two radio telescopes

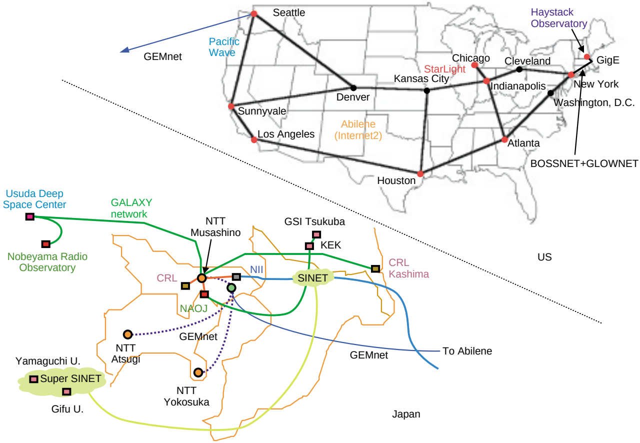

Fig. 4. GALAXY/GEMnet and partner R&E networks.

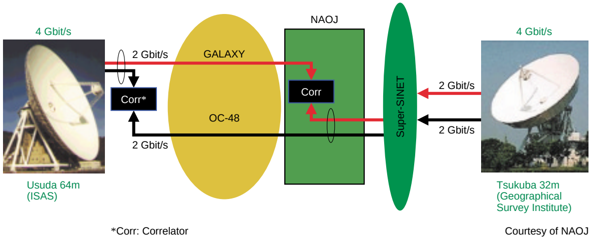

Fig. 5. Collaboration with Super SINET (4-Gbit/s real-time experiment).

and correlator sites must participate in the experiment. This requires good collaboration among the personnel operating the equipment at the sites. Typical mistakes include failing to target the telescope at the right radio source, mismatching the observation frequency bands, and misconnecting some of the large number of cables. To test the system setup within the limited time available, it is essential to use efficient communications tools.

To test the effectiveness of multimedia conferencing systems in these distributed laboratory environments, we have started to deploy a high-quality video conferencing system in the main experimental sites. The quality of both video and sound should be as good as possible to capture the environment of other locations not only in terms of the spoken words, but also the background noise and visual atmosphere. We are using MPEG2 encoders/decoders, echo cancellers, and large-screen plasma displays to create a high-quality cooperative working environment.

4. IP data transfer system and supporting tools

4.1 IP transfer system for real-time VLBI

Although the use of IP for transferring VLBI data brings increased connectivity with other sites, it presents us with many challenging research issues including the high-speed stream transmission scheme in the presence of relatively large latency and packet losses. We developed the IP data transfer system using parallel IP streams using commercial personal computers (PCs) and special purpose hardware to attempt to solve this particular technical problem. This system achieves flexible scalability in transfer rate by increasing the number of PCs used. High throughput is achieved by using multiple streams to avoid the throughput degradation caused by large propagation delays. UDP (User Datagram Protocol) or TCP transfer can be selected depending on the conditions of the network to be used for the observation.

The basic idea of this equipment is to replace the K4 digital interface, which is based on the ID1 standard specification connecting the observation equipment and data recorder with the developed system. K4 is used for the KSP and this IP-based system can replace the conventional data recorder or ATM transmission system. The configuration of the developed system is shown in Fig. 6. The implementation approach was to use commercial PCs with additional special purpose hardware to interface between the PCs and observation equipment. This will let us increase the transfer rate by adding more low-cost PCs.

The IP transfer system consists of an ID1 parallelizer, an ID1 serializer, IP-transmitting PCs, and IP-receiving PCs. The ID1 parallelizer receives the data stream from the sampler through the ID1 interface, and divides it into multiple IEEE1394 streams. Each IP-transmitting PC receives the IEEE 1394 stream, extracts observation data, and transmits it in IP packets. On receiving the IP packets, each IP-receiving PC extracts observation data and transfers it to the ID1 serializer in an IEEE 1394 stream. By receiving the IEEE 1394 data streams from the IP-receiving PCs, the ID1 serializer reconstructs the observation data and sends it to the cross correlator through the ID1

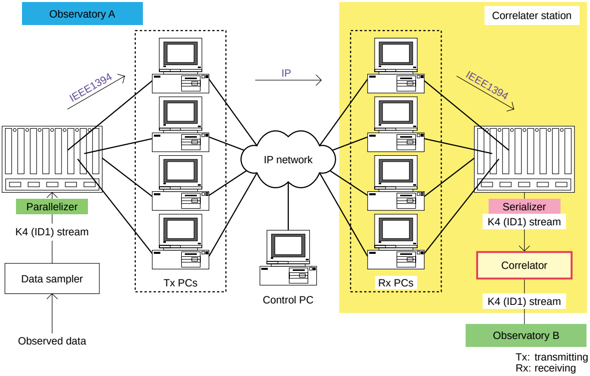

Fig. 6. Multiple stream VLBI data transfer system.

interface. The correlator can perform the necessary calculations by receiving other observation data through other IP transfer systems.

4.2 Implementation

We developed two special purpose items of hardware: ID1 parallelizers and ID1 serializers (Fig. 7). They can handle up to 16 data streams and the maximum rate is 256 Mbit/s per chassis. The speed is limited only by the ID1 specification and can upgraded by replacing the ID1 interface with a faster communications interface. It is also possible to transmit the data stream at a higher speed by stacking several chassis using multiple ID1 interfaces. The IP-transmitting and IP-receiving PCs are inexpensive Pentium2/400 PCs running Linux 2.4.6. On these PCs, we implemented application software in C language to send and receive IEEE1394 and IP packets.

Each IP-transmitting PC receives data in an IEEE 1394 data stream and transmits it in TCP/IP or UDP/IP packets depending on the operating mode to the corresponding IP-receiving PC, which extracts data from the received packets and sends it to an IEEE 1394 interface. Accordingly, multiple TCP/UDP sessions are set up between the IP-transmitting PCs and IP-receiving PCs. A parallel transfer scheme must guarantee that data is correctly ordered. This system uses a round robin style for the ID1 parallelizer and serializer to ensure that the data obtained from the ID1 serializer is the same as that input to the ID1 parallelizer.

One important issue that needs to be considered is the possibility of packet loss in UDP mode caused by UDP's lack of a retransmission mechanism. Packet losses hamper the reconstruction of the original data stream at the ID1 serializer. To solve this problem, we insert random data of the same size at the IP-receiving PC when a packet loss is detected. Packet loss at the receiving end is detected by inserting a sequence number at the beginning of each payload of UDP packets. This measure causes no harm to cross correlation because the cross correlation will not be influenced by the insertion of dummy data as long as the accurate time alignment is preserved.

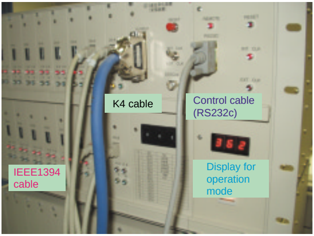

Fig. 7. Outside view of serializer unit.

Using this data transfer system, we conducted several experiments during 2001 and 2002. The system successfully transmitted VLBI data at 256 Mbit/s. The actual observation using the system was only done at 128 Mbit/s though, due to the limitation of the radio telescope's observation equipment. In the experiment, observation data at Usuda was transmitted to Musashino R&D Center by the IP transfer system at 128 Mbit/s. At the same time, another stream of observation data was sent from Kashima to Musashino by ATM transfer. By cross-correlation processing at Musashino, we confirmed fringes. This was the first successful experiment in the world on real-time VLBI observation based on high-speed IP transfer.

5. Conclusions and future plans

Besides developing the IP data transfer system, we are also pursuing absolute sensitivity with the help of much higher data rates. In June 2001, we successfully achieved the world's first real-time VLBI observation with a processing speed of 1 Gbit/s, using the Usuda and Kashima antennas. This achievement has great significance in opening up a new vista in VLBI radio astronomy by improving the detection sensitivity of the observation system. The ability to detect very weak radio sources will also accelerate studies on constructing a space-time standard infrastructure in space, which is being undertaken by CRL, including real-time and high time-resolution determination of earth orientation parameters.

In December 2002 we successfully achieved transmission and processing speeds of 2 Gbit/s. The development of "Internet VLBI" systems and a distributed cross-correlation system using networked computers are other targets. With the success of IP VLBI data transmission, the possibility of making an international real-time VLBI observation system appears realistic. In addition, the combination of distributed data analyses and IP data transmission/packet routing should lead to a completely new type of VLBI observation. For example, IP multicast could be used to distribute observed radio signals to a large number of cross correlators in the Internet, many of which will be ordinary PCs equipped with mathematical software conducting necessary scientific calculations on demand. In combination with the multistream data transfer method described in this paper, very-high-speed distributed cross correlation will be possible.

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