19.14 PRINCIPLES OF RADAR OPERATION OVER THE INTERNET: THE VCHILL

V. Chandrasekar*, Yoong-Goog Cho, D. Brunkow, and A. Jayasumana
Colorado State University

1. Introduction

The Colorado State University (CSU)-CHILL radar system is a National Facility operated under a cooperative agreement with National Science Foundation to support education and research in remote sensing of the atmosphere. The CSU-CHILL radar is an S-band fully polarimetric Doppler radar with polarization agility and diversity (Brunkow et al. (2000)). A fully polarimetric radar computes the full covariance matrix of each radar resolution volume. The full covariance matrix provides a complete set of measurements on the observation volume. The radar system consists of a unique two transmitter design that can be used to transmit either horizontal and vertical polarization state on a switched mode, or a combined slant linear, or elliptical polarization state. The polarization states of the receiver are always fixed at horizontal/vertical independent of the transmit mode. The CSU-CHILL radar has been continuously upgraded to enhance its functionality and to provide the research communities with high quality data with advanced capabilities (Brunkow (1999)). The data generated from the CSU-CHILL radar system have been being used by many universities and research communities over the United States for educational and research activities.

In 1997, CSU launched an initiative to enable the real-time operation of the CSU-CHILL radar over the Internet. The goal of this project named as Virtual CHILL (VCHILL) is to extend the educational and research experiences of CSU-CHILL via the network infrastructure and enhanced computing capability to remote locations (Chandrasekar et al. (2001)). The concept of the VCHILL has been implemented at two levels, namely, low-bandwidth VCHILL and high-bandwidth VCHILL, depending on the required bandwidth of the network for the data transmission as shown in Fig. 1. The low-bandwidth VCHILL transfers either the archived or the real-time radar parameters, which corresponds to a subset of the covariance matrix, to the remote sites for display and further end-user applications. A more advanced low-bandwidth application is an active mode, where radar control is transferred to a remote location enabling the remote users to control the radar operation over the Internet. The data transmission in these modes requires a bandwidth of the order of fraction of one Mbps, and therefore it is referred to as a low-bandwidth VCHILL.

The high-bandwidth VCHILL provides the remote users with the CSU-CHILL radar experience at a higher level so that the signal processing and the control of radar parameter computation algorithm are moved to the remote-user sites (Chandrasekar et al. (2001)). The radar signals digitized using an exclusive parallel receiver are transferred to the remote sites over high-bandwidth data network, such as Next Generation Internet (NGI). Therefore the estimation process of the covariance matrix is physically and logically separated from the radar. The main purpose of the high-bandwidth VCHILL is to provide the environment wherein the remote users process the Digitized Radar Signal (DRS) according to their specifications and evaluate their algorithms. This is primarily for research and graduate education applications. The radar parameters are estimated at the remote sites and can be delivered to other display nodes using the low-bandwidth VCHILL technology. The transmission of the DRS requires much higher bandwidth of the order of several hundreds Mbps as compared to the low-bandwidth VCHILL, which is why it is referred to as the high-bandwidth VCHILL.

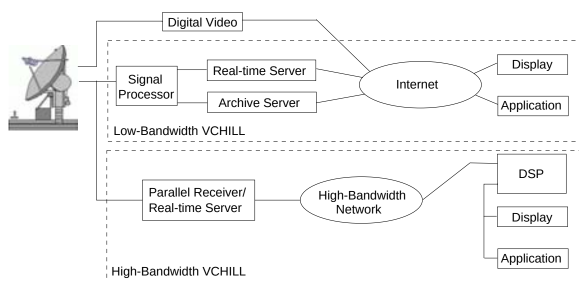

Figure 1: Conceptual diagram of the VCHILL.

This is certainly a paradigm shift as compared to the traditional way of the radar operation and data collection, in which the researchers had to be physically present at the facility to operate the radar and get the data in storage media at the end of data collection process. Currently, the VCHILL is providing universities and research communities over the United States with easy access to the radar facility. The use of the low-bandwidth VCHILL greatly helps radar education by enhancing the understanding of the operating principles and applications of the pulsed-

*Corresponding author address: V. Chandrasekar, Dept. of ECE, Colorado State University, 1373 Campus Delivery, Fort Collins, CO 80523; email: chandra@engr.colostate.edu

Doppler weather radar system in their class room. Furthermore a new Java version of the application program has just been released, which can operate independent of the computing platform and is expected to improve portability and accessibility to the low-bandwidth VCHILL. In addition, the concept of the high-bandwidth VCHILL has been experimentally validated on a test bed at CSU. This paper describes the architecture validated for the VCHILL, data transmission over the Internet, and the challenges for developing the high-bandwidth VCHILL, as well as future opportunities.

2. Low-bandwidth VCHILL

a. System architecture

The existing signal processor and data system of the CSU-CHILL radar were developed based on high speed signal processor chips performing most of the covariance matrix computation. Figure 2 shows the block diagram describing the signal processing and data system (Brunkow (1999)). The ASPEN/DRX processors digitize the 10-MHz IF signal from the vertical and horizontal channels and produce Inphase and Quadrature components of the digitized radar signals. A DSP card, which contains two SHARC processors, calculates the various radar parameters from the digitized signals. The VME host operates as a real-time server with VxWorks environment. The parameters calculated by the processor are transferred by the VME host to other remote systems for display and further user applications. For the future use, the data from the VME host can be transferred simultaneously to an archive network server, and saved in a mass storage device.

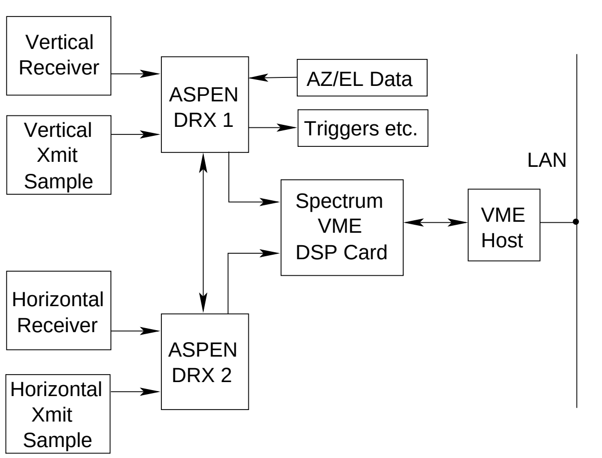

Figure 2: Block diagram showing the existing data system of the CHILL radar.

Users at the remote sites are able to connect to either the real-time server or the archive server over the Internet depending on their requirement as shown in Fig. 3. The Graphic User Interface (GUI) provides the users at remote locations with the ability to connect to the servers and display the radar parameters of interest on their screen as shown in Fig. 4. All necessary programs including support documents for installation and operation can be downloaded from the CSU-CHILL radar website (http://www.chill.colostate.edu/java/).

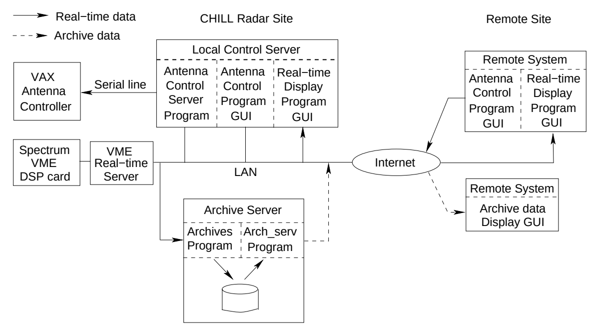

Figure 3: Block diagram showing the data transmission for the low-bandwidth VCHILL. The remote users can connect to either the VME real-time server or the archive server. Moreover they can control the antenna of the CSU-CHILL radar system in real time.

b. Data transmission

A user payload transmitted over the Internet for displaying a ray of data consists of a header and a string of covariance matrix parameters. The header that precedes the data set of a parameter contains information for display. Let the scan rate be Φ deg/sec, angular resolution between display be $\Delta\phi$, size of the header be D_{header}, and the number of range samples be N. The bandwidth required (BW) (Bytes/sec) for the transmission of a single parameter can be estimated as

$$BW \quad = \quad (\frac{D_{header} + N}{\Delta\phi})\Phi. \tag{1}$$

For example, consider the following typical radar operating conditions; a) Φ is 10 degrees/sec, b) $\Delta\phi$ is 0.75 degrees, c) N are 1000, and d) D_{header} is 150 bytes. The bandwidth required for the transmission of a single parameter for this case is approximately 122.7 Kbps. It is assumed that one covariance matrix parameter for each range occupies one byte of data. This bandwidth requirement is low enough for the typical Internet to support the real-time applications of the low-bandwidth VCHILL. Currently, the Internet's Transmission Control Protocol (TCP), which provides a reliable, connection-oriented, and byte-stream service, is being used as the underlying transport layer protocol.

c. User operations

The application programs at the remote sites for the access to the low-bandwidth VCHILL servers were initiated

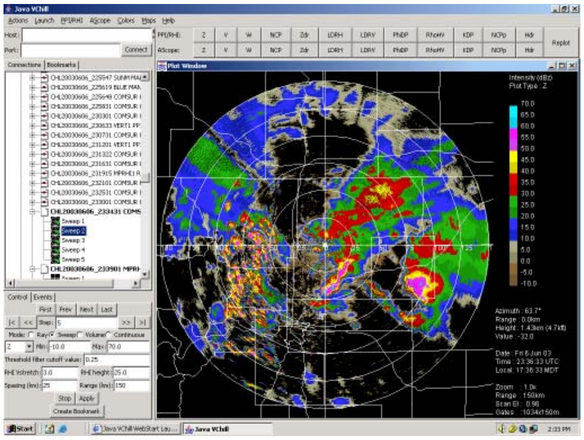

Figure 4: GUI windows showing a reflectivity. The GUI can display the radar parameters listed on the top row and right-hand side in real time or archival mode. The remote users select the parameters of interest by clicking the corresponding icons. It can also display either PPI or RHI depending on the scanning mode. For the archival mode, the remote users can look at the data available in the server (upper part and left-hand side) and set the display mode (lower part and left-hand side).

on the Sun/Solaris platform. At present, a Java version, which is relying on the object oriented design principles such as modularity and design by contract, has been developed. The Java version is able to operate on numerous platforms, which enhances portability in operating the application programs at the remote site. The program is designed to be run through Java WebStart, which allows the end users to start the latest version of the program with a single click on a website hyperlink. It will also support an arbitrary number of simultaneous TCP connections to the server, including other enhanced display functionalities.

Once the users connect to the archive server, they are able to look at the archive list, which allows them to select the specific sets for display as shown in Fig. 4. They can also select the parameters of interest to them in the GUI window. The GUI provides various options for analysis and display, such as beam by beam view, sweep, volume, and continuous play back modes. Moreover, the users can optimize the display configuration options, such as magnification, location and display scales.

For the real-time operation, the users are required to register in advance. The registration process provides the CSU-CHILL staffs with the information of the remote users, for example, institution and application of the VCHILL. The users can display the real-time radar observations and control the scanning of the antenna and display system by selecting application options. There is a control server that can connect with clients running anywhere on the Internet. When a request for the radar operation and data transmission is received, the control server checks the record database and grants permission based on policy and protocol consistent with the mission of the facility. As soon as the permission is granted, the radar console is transferred virtually to the remote location so that the user is able to control the radar. Currently, the GUI that is operating at the remote sites includes control section, scan segment editing section, processor settings, and status display section. All of the useful radar scan parameters, such as PRF and pulse length, are under control of the remote user. One complete setting of these parameters is saved in each scan segment in the antenna controller. These scan segments can be viewed, modified, and run as needed under the control of the remote operator. Therefore, the radar system can be controlled either interactively or via preprogrammed scanning options. Similarly, the users can select the radar parameters as well as change the display configurations. In addition, a digital video system for displaying the real-time radar activity such as antenna movement and an audio/video conferencing system are available to enhance the effect of the VCHILL applications.

The CSU-CHILL Radar facility routinely conducts virtual tours of the facility over the Internet. Usually, the visitors are radar meteorology or engineering students at a remote location or from a course remotely offered at a conference. To conduct these tours, the digital video terminal is set up at the remote classroom. This connects to a similar unit at the radar to allow the tour providers and visitors to see and talk to each other. This networked meeting session is usually projected on one screen at the classroom. On the second screen, the GUI is demonstrated. This GUI screen can also be used to show live video from several video cameras around the radar site. In this way, the visitors can see the antenna move when a scan is started on the radar remote control system.

The low-bandwidth VCHILL has been used for in-class instructions at University of Washington, Texas A&M, as well as University of Alabama at Huntsville for instrumentation and radar meteorology courses. The students had the ability to control the CSU-CHILL radar and display the various radar parameters in a class room setting. The audio/video conferencing system was simultaneously used for communication between the CSU-CHILL radar site and the class. The AMS Short Course during the 31st Radar Conference in Seattle (August 2003) was conducted totally using the low-bandwidth VCHILL. This method of delivery had the same impact as if the course was taught at CSU right at the radar site. The demonstration of the remote operation of the CSU-CHILL radar over the Internet greatly helped the students enhance their understanding of the principles and applications of the weather radar system. The practitioners who registered for the Short Course also participated in laboratory sessions working with the archive applications of the low-bandwidth VCHILL, thereby fundamentally changing the paradigm of radar education.

3. High-bandwidth VCHILL

a. Technical challenges

In the context of the high-bandwidth VCHILL, the covariance matrix computation is performed at the remote sites, which is the main difference as compared to the low-bandwidth VCHILL. The DRS generated at the radar is transferred to the remote sites, where the radar parameters are estimated and delivered to other display nodes, over high-bandwidth data network. In a multi-user environment, in particular, each remote user can independently process the same DRS in real time for various research applications, such as clutter filtering and spectral processing. They can also keep the connection of the low-bandwidth VCHILL during the operation of the high-bandwidth VCHILL at the same time. Therefore, the remote users can compare their operation using their own algorithms against the computations done at the radar site. The networked approach to the radar signal processing at the remote sites is likely to enhance not only the educational experience, but also developments of innovative research applications.

The design and implementation for realizing the high-bandwidth VCHILL presents various technical challenges, such as strict real-time requirements for manipulating DRS and signal processing, demand for large bandwidth, and variable latencies introduced by physical distances, router delays and end-system performances. The rate at which data is generated by a receiver is generally determined by a combination of factors relating to quantization level, sampling rate, and number of receive channels. The data rate is typically three orders of magnitude higher than that of the low-bandwidth VCHILL. For example, the data rate is about 64 Mbps for a dual channel coherent receiver system sampling at 1 MHz with a quantization level of 16 bits under the assumption that pulse repetition time (PRT) is 1 msec. The data rate increases to 320 Mbps for 5 MHz sampling rate. The end systems for transmitting the DRS and computing the radar parameters should be designed so as to provide high Quality of Service (QoS). Because of the high data rate, lack of the required bandwidth for the transmission can often affect the performance of the high-bandwidth VCHILL application. Therefore, the application programs should be intelligent enough to accommodate the various demands.

b. End systems

To achieve sufficient flexibility in the high-bandwidth VCHILL, a new digital receiver system was designed to operate in parallel with the existing DRX signal processor as shown in Fig. 5 (Cho (2004)). After extensive analysis, an independent receiver that would serve the high-bandwidth VCHILL system exclusively was determined to be the best way to implement its concept without extensively compromising numerous innovative aspects of the high-bandwidth VCHILL. Development of this new digital-IF parallel receiver for the CSU-CHILL radar combined with innovative data manipulation protocol for the transmission of the DRS lays the foundation for the high-bandwidth VCHILL. The parallel receiver functions as a part of the DRS server concept in networked environment so that it integrates all input data into a specified format in real time. The demands of the pulsed-Doppler polarimetric radar operation and the high data rate require extreme care in synchronizing data acquisition and high-speed data integration and manipulation.

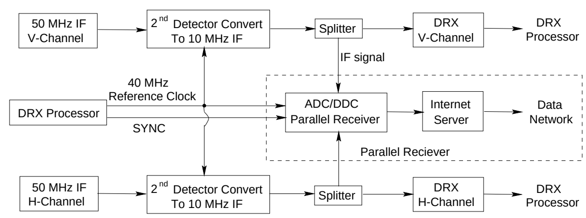

Figure 5: Block diagram of the parallel receiver of CSU-CHILL radar. ADC stands for Analog-to-Digital Conversion and DDC means Digital Down-converter. Down-converted IF radar signals split from the DRX receive channel go to the ADC/DDC receiver. Reference clock and SYNC signal generated in the DRX processor are shared with the parallel receiver. The parallel receiver operates as a network server and transmits the DRS over data network.

The end-system architectures for transmitting DRS over high-bandwidth network and computing radar parameters at the remote sites were designed based on the client-server model relying on the operation of multiprocesses and multithreads as shown in Fig. 6 (Cho (2004)). The key functionalities of the end systems, such as the data acquisition and transmission of the data on the DRS server, as well as the radar parameter computation and transfer on the DRS client, are divided into multiple processes that operate at the same time. This modularization also simplifies upgrading or innovating any functionality in the future. In addition, generic packet structures and data structures for the information sharing between processes were designed to be compatible with the operating principles of a pulsed-Doppler radar system. The high-bandwidth VCHILL was implemented on a Linux operating system and evaluated in real-time using a test bed at CSU. The implementation and network protocols can support the real-time operation of the CSU-CHILL radar up to data rates of 294 Mbps, which is equivalent to the sampling rate of 5 MHz with PRT of 1.05 msec. Currently experiments using high-bandwidth applications are being utilized by several users.

c. Data transmission

It is meaningful to mention the Internet's transport-layer protocols in connection with the real-time applications of

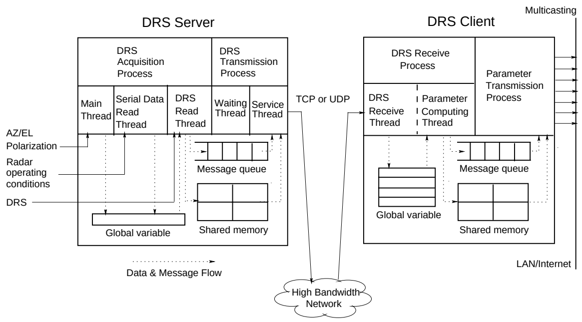

Figure 6: Overall end-system architectures for the transmission of the digitized radar signal, the computation of radar parameters, and the delivery of parameters to multiple display nodes and further applications.

the high-bandwidth VCHILL. The most commonly used protocol is TCP, which provides a reliable, connection-oriented service to the applications as mentioned earlier. The TCP throughput is determined, in general, by segment size, round trip time and packet loss rate (Widmer et al. (2001)). Therefore, long round trip time delay and multiple packet losses caused by heavy network traffic load frequently degrade the end-to-end throughput and might lead to failure in satisfying the real-time requirements of the high-bandwidth VCHILL. However, TCP is sufficient for the low-bandwidth VCHILL.

Consequently, Internet's User Datagram Protocol (UDP), which provides an unreliable and connectionless service, was considered as an alternate transport-layer protocol for the high-bandwidth VCHILL. However, due to the unreliability and connectionlessness, packets transmitted over UDP are dropped occasionally in a random fashion (Stevens (1998)) so that the transmission over UDP degraded the QoS of the end-user applications. Another drawback of UDP is that it lacks congestion control and flow control mechanisms, which also invokes the issue of fairness among the connections that share the same bandwidth resources (Floyd and Fall (1999)). To mitigate effects of the drawbacks the application programs require additional functions of the transport-layer protocol, such as the guarantee of delivery and the congestion control. An application-level network protocol has been developed to transmit the real-time DRS over UDP. The DRS server adapts the transmission rate to the available bandwidth according to the feedback from the DRS client. The protocol employs data selection schemes to provide the highest quality of the estimated radar parameters possible under given network conditions.

4. Future opportunities

Numerous developments have been being carried out enabled by the high-bandwidth VCHILL initiative. One of these is the development of application-level network protocols for congestion control and waveform design. It will make the real-time operation tolerable and provide high quality end products under varying network conditions. The developed protocols were implemented on a PC platform networked with a Gigabit Ethernet. Performance evaluation using a test bed at CSU clearly shows that the DRS server adapts the transmission rate to the available bandwidth. Quality of the display is also greatly improved compared to that obtained without application-level protocols. In addition, distribution of DRS using multicasting protocol over the high-bandwidth data network has been developed. Thus the VCHILL initiative has advanced the sharing of CSU-CHILL experience nationally and internationally over the Internet.

5. Summary and Conclusion

The VCHILL project is an initiative to enable radar operation over the Internet. This initiative has two parts, namely the low-bandwidth VCHILL and the high-bandwidth VCHILL. With the low-bandwidth VCHILL, the radar parameters estimated at the radar site are delivered to any location that has the Internet connectivity and displayed either in real time or archive mode. The radar console is also virtually transferred to the remote site. The graphic user interface allows the remote users to fully control the radar system as well as the display options. The low-bandwidth VCHILL is actively being used as a part of classroom instruction to enhance the understanding of pulsed-Doppler radar. The Java version of the VCHILL application programs provides the end users with more portability and flexibility in accessing the low-bandwidth VCHILL system.

The goal of the high-bandwidth VCHILL is to provide the remote users with a higher level of radar experience including manipulating the signal processor applications. Implementation of the high-bandwidth VCHILL presents various challenges, such as strict real-time requirements for manipulating the DRS and signal processing, as well as tolerance to variable latencies and deficiency of available bandwidth for data transmission. An exclusive parallel receiver was developed for supporting the innovative aspects of the high-bandwidth VCHILL. End systems for the synchronous data acquisition, transmission, and computations are designed based upon the multiprocess and multithread operation to meet the requirements of high bandwidth real-time operation. The systems implemented on the PC platform with Linux operating system was experimentally validated on the test bed at CSU over the Gigabit Ethernet. Further development of the VCHILL will continue to provide new opportunities in radar research and education.

6. Acknowledgment

This research is supported by the National Science Foundation ITR Program. The CSU-CHILL facility is operated by through a cooperative agreement with NSF. The authors acknowledge the excellent support provided by the CSU-CHILL staff (Mr. Patrick Kennedy and Mr. Robert Bowie) for the research work presented here. The authors also acknowledge the other Co-PIs of the facility, namely Dr. Steven Rutledge and Dr. V. N. Bringi.

References

Brunkow, D., V. N. Bringi, P. C. Kennedy, S. A. Rutledge, V. Chandrasekar, E. A. Mueller, and R. K. Bowie: 2000, A description of the CSU-CHILL National Radar Facility. *Journal of Atmospheric and Oceanic Technology*, **17**, 1596–1608.

Brunkow, D. A.: 1999, A new receiver and signal processor for the CSU-CHILL radar. *The 29th International Conference on Radar Meteorology*, 256–258.

Chandrasekar, V., D. Brunkow, and A. P. Jayasumana: 2001, CSU-CHILL operation over the Internet: Virtual CSU-CHILL. *The 30th International Conference on Radar Meteorology*, 58–60.

Cho, Y.-G.: 2004, *A high-bandwidth radar operation over the Internet: Signal analysis, network protocols and experimental validation*. Ph.D. thesis, Colorado State University, Fort Collins, Colorado.

Floyd, S. and K. Fall: 1999, Promoting the use of end-to-end congestion control in the internet. *IEEE/ACM Transactions on Networking*, **7**, 458–472.

Stevens, W. R.: 1998, *UNIX Network Programming Vol. 1: Networking APIs: Sockets and XTI*. Prentice-Hall, Inc., 2nd edition.

Widmer, J., R. Denda, and M. Mauve: 2001, A survey on TCP-Friendly congestion control. *IEEE Network*, 28–37.