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LLNL-TR-747978

Gigabit Networking Technology Final Report CRADA No. TC-299-92

W. J. Lennon, N. L. Schryer

March 16, 2018

Disclaimer

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Gigabit Networking Technology

Final Report

CRADA No. TC-299-92

Date: April 28, 1997	TACT: CA+A	Revision 1.0

A. Parties

The project is a relationship between the Lawrence Livermore National Laboratory (LLNL) and AT&T Bell Laboratories.

University of California
Lawrence Livermore National Laboratory
7000 East Avenue, L-795
Livermore, CA 94550

AT&T Bell Labs
Murray Hill
NJ, 07974

B. Project Scope

The Gigabit Networking Technology project was composed of four separate but complementary CRADA efforts which sought to develop, test, and evaluate alternate approaches to interconnecting gigabit LANs and WANs. The goal of the Gigabit Networking Technology project was to test, demonstrate, and evaluate some of the most promising components of cutting-edge telecommunication technologies that will directly support defense and energy applications, as well as many commercial and scientific interests. LLNL, the other participating laboratories, DOE, and the nation will benefit greatly from this CRADA because interconnected gigabit LANs and WANs will be the technology infrastructure that will make possible the "information super-highway."

LLNL's specific CRADA goals were to investigate

- Fibre Channel LAN/WAN routing, i.e. "internetworking"
- Fibre Channel LAN inter-connections over ATM and SONET communication systems
- Promote Driving Applications
  - Scientific collaborations
  - Scientific visualization
  - Teleconferencing
- Collaborations with other XUNET participants to test the technical issues posed by LAN/WAN inter-connections and inter-networking.

A. There were four explicit deliverables in LLNL's CRADA (listed in priority order).

1. LLNL would develop the necessary adapters so that Fibre Channel (FC) Gbps LAN's might be interconnected using the complementary standard WAN protocols, SONET and ATM.

2. LLNL would recruit scaleable applications for AT&T's experimental university network, XUNET, to provide volunteer traffic to illuminate WAN requirements. Recruit similar collaborations across the four DOE/DP laboratories.

3. LLNL would determine ATM Adaptation Layer protocol needs for all currently proposed FC upper-level protocols carried by the ANSI FC 3.0 physical layer proposed standard, currently undergoing public review.

4. LLNL would cooperate with AT&T, XUNET research partners, and the three other DOE/DP laboratories to compare the effectiveness of different inter-LAN transport mechanisms. LLNL would lead the study of FC transport.

C. Technical

Fiber Channel Internetworking Adapters

The project investigated two types of Fibre Channel internetworking strategies, Bridging of Fibre Channel over ATM fabrics and Fibre Channel transport over SONET. A common issue to both investigations was the issue of speed mismatch between Fibre Channel and the WAN transports (ATM or SONET) speeds.

Bridging is a term describing the physical connection of two physically separate networks into a single network. This CRADA studied Fibre Channel Bridging over ATM fabrics. The study evaluated bridging at FC-1 and FC-2 protocol layers. The question of terminating and nonterminating Fibre Channel bridge architectures was also addressed. It was concluded that marketing and application specific considerations would favor one architecture over another. For example, a Bridge architecture designed for "low cost connectivity" and not maximum performance would most likely be a nonterminating FC-1 architecture. However, if "high performance connectivity" is emphasized, then the Bridge architecture would tend to look like a more costly terminating FC-2 architecture.

Fibre Channel transport over SONET OC3 or OC12 was also studied. This assumed transparent (or near-transparent) mapping from the FC data stream into the SONET payload without terminating the FC at each end as would be the case with a bridging design. The purpose of FC over SONET would be to allow interconnecting disjoint enterprise FC networks via the SONET-based public telecomm/datacomm networks. The goal of FC over SONET would be to maximize data flow with minimal impact due to time-of-flight propagation delays. Alternate intermediate mappings such as FC to ATM to SONET would impose both the relatively high overhead transmission of ATM as well as that of FC. Two problem areas were addressed. The first issue was to optimize the bit mapping of 266 and 1062 megabit per second FC into the SONET rates which are multiples of 155.5 Mbps. The second problem area was the need to accommodate the much longer roundtrip propagation times encountered in longhaul and WAN applications.

Various mapping schemes were developed and assessed. Two classes of mapping schemes were investigated — transparent and nontransparent. Transparent mapping schemes result in a one-to-one symbol mapping with no loss of data and minimal additional buffering at the SONET interface. Nontransparent mapping schemes result in some elimination of data in the bitstream and may require additional buffering and hence buffer throughput delay at the SONET interface. The minimal mapping scheme was determined to be a 9 bit mapping. The resultant mapping into SONET payload (data) space was still highly inefficient when transparently mapping the data stream; i.e. at least two SONET channels were required to map every one FC266 channel.

Nontransparent mapping schemes take advantage of a key observation: most FC data links tested in the literature were unable to achieve more than approximately 50–70% of the maximum channel rate throughput due to limitations in platform hardware design and software implementation so that

idle sequences are inserted to maintain the baseline 266 Mbps bit rate. In nontransparent mapping schemes the incoming FC traffic is buffered and monitored to remove these long streams of idle sequences.

The key observations made in the area of Fibre Channel to SONET adapters was that the combination of mapping inefficiencies and buffer memory constraints in the longhaul and WAN environment present critical obstacles to successful deployment of simple mapping adapters and that bridging should prove to be a more cost effective, higher throughput alternative.

WAN Collaborations

The XUNET network was used to allow researchers at LLNL and other XUNET sites to communicate much faster than was possible over the Internet. The XUNET provided a high availability DS3 (45 Mbit) cross-country ATM network. Local access was via FDDI (100 Mbit) connections to XUNET routers.

The most notable application demonstration was when Vice President Al Gore observed from AT&T, Murray Hill a visualization of a vector field produced here in Livermore and transmitted over the XUNET ATM network. This was an impressive demonstration of remote scientific computing and scientific visualization.

LLNL and AT&T material scientists used the XUNET to facilitate their materials research.

We worked with Sandia National Laboratory (Livermore), the LLNL Education Program, and XUNET collaborators at UIUC to build a high speed link over XUNET between the education super computer and a high school in the Champagne-Urban Illinois area.

A common observation made by the XUNET research community following the collaborative demonstrations was that existing computer workstations, common applications, and software protocols were limiting the performance of long distance collaborative applications. Systems and applications are typically designed to work within ethernet-like environments. Applications are limited in their ability to capitalize on network improvements due to limitations in the computer systems and network protocols. Performance as seen by the end users is a complex systems problem involving workstations, operating systems, networking protocols, and network speed. Fortunately, vendors are improving all aspects of the system so as to take advantage of the improvement in network speeds.

FC Protocols

We invested little project effort on the development of new FC protocols. Instead, we leveraged existing LLNL participation in ANSI FC standards committees to monitor the progress of protocol development. By the end of the CRADA, the ANSI FC committees' ratification process for highter level protocols was just beginning.

Collaborations to test the effectiveness of FC LANS

Collaborations to test the effectiveness of FC LANS was our lowest priority task. It was a low priority since we deemed it too difficult to complete due to limited hardware availability. This expectation was born out in fact. Hardware development by vendors was slow in coming and often plagued with bugs and standards incompatibilities between vendors.

We were able to demonstrate a Fibre Channel application involving disk shadowing over a long distance link between LLNL and UC Berkeley. We were also able to study the general problem of LAN interconnect via Fibre Channel technology.

D. Partner Contribution

AT&T designed, implemented and operated the experimental XUNET ATM network. This network stretched from Livermore in California to Murry Hill in New Jersey. Other XUNET Research Community sites were the following:

Columbia University
Lawrence Berkeley Laboratory
Rutgers University
Sandia National Laboratory (Livermore)
University Illinois
University of Calif. Berkeley
University Wisconsin

In addition to the on-going operation of the network, AT&T organized a yearly conference of researchers.

E. Documents/Reference List

Reports

- CRADA Quarterly Reports
- TACT Review 3/94
- TACT Review 9/94
- "Bridging Fibre Channel over ATM Fabrics"

Presentations

• Gigabit Network Technology	Presentation to DOE
• Metric Gigabit	1994 XUNET Student Conference
• LAN and WAN Activities at LLNL	1995 XUNET Student Conference

ANSI Fibre Channel Standards

- FC-PH
- FC-AL
- FC-IP
- PC-LE

There are no patents, copyrights, or inventions arising from this CRADA. No protected CRADA information was generated by this CRADA.

F. Acknowledgment

Participant's signature of the final report indicates the following:

1) The Participant has reviewed the final report and concurs with the statements made therein.

2) The Participant agrees that any modifications or changes from the initial proposal were discussed and agreed to during the term of the project.

3) The Participant certifies that all reports either completed or in process are listed and all subject inventions and the associated intellectual property protection measures attributable to the project have been disclosed or are included on a list attached to this report.

4) The Participant certifies that if real property was exchanged during the agreement, all has either been returned to the initial custodian or transferred permanently.

5) The Participant certifies that proprietary information has been returned or destroyed by LLNL.

Norman L. Schryer 12/2/97
Norman L. Schryer Date
AT&T Bell Labs

William J. Lennon Date
Lawrence Livermore National Laboratory

Attachment I – Final Abstract
Attachment II – Project Accomplishments Summary
Attachment III – Final Quarterly Report

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Participant's signature of the final report indicates the following:

1) The Participant has reviewed the final report and concurs with the statements made therein.

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Norman L. Schryer 12/2/97 Date
AT&T Bell Labs

William J. Lennon 1/29/98 Date
Lawrence Livermore National Laboratory

Attachment I – Final Abstract
Attachment II – Project Accomplishments Summary
Attachment III – Final Quarterly Report

Gigabit Networking Technology

Final Abstract
Attachment I
CRADA No. TC-0299-92

Lawrence Livermore National Laboratory (LLNL) entered into an agreement with AT&T Bell Laboratories to develop Gigabit per second Local Area Network Systems (LANS) and Wide Area Networks Systems (WANS) technologies. Interconnected gigabit LANs are the infrastructure for future technology commercialization interchange and are expected to be one of the key elements supporting commerce in the latter part of the decade. In the technology arena, gigabit LANS will support engineers and scientists using techniques such as scientific visualization, access to remotely sited resources and peers who are geographically distant. LLNL is one of four Defense Program laboratories that have entered into a set of complementary research activities to test and evaluate some of the most promising components of the coming revolution in the country's communication infrastructure.

Lawrence Livermore National Laboratory is operated by the University of California for the U.S. Department of Energy
Technical Transfer Initiatives Program, P.O. Box 808 L-795, Livermore, CA 94551

Gigabit Networking Technology

Project Accomplishments Summary (Attachment II)

CRADA No. TC-0299-92

Date: April 28, 1997 | TACT CA+A | Revision 1.0

A. Parties

The CRADA is a relationship between the Lawrence Livermore National Laboratory (LLNL) and AT&T Bell Laboratories.

University of California
Lawrence Livermore National Laboratory
7000 East Avenue, L-795
Livermore, CA 94550

AT&T Bell Labs
Murray Hill
NJ, 07974

Other organizations involved with the XUNET research network but not party to this CRADA were:

Columbia University
Lawrence Berkeley Laboratory
Rutgers University
Sandia National Laboratory (Livermore)
University of Illinois
University of California, Berkeley
University of Wisconsin

B. Background

Today's computing and communication needs exceed the capabilities of installed networks. This is particularly true for DOE/DP modelers and analysts. Continuing improvements in capacity, size, and speed are required in high performance computers, storage systems, and networks. This project focuses on Gigabit per second (Gbps) networks, an essential infrastructure for the development and deployment of high performance systems and applications.

A. Network developers are addressing the communication/networking problems posed by high performance systems and applications with two very different approaches.

1. Telecommunications designers seek to smooth peak demands. They rely on statistical multiplexing, and tolerate latencies and data loss in order to optimize what experience dictates is their critical resource, the communication channel utilization.

2. Computer systems designers minimize latency and design for peak bandwidth. They tolerate low channel utilization in order to optimize their critical resources, large data stores and high speed computers.

B. Space Division Multiplexing is a cost effective solution to implementing Gbps LAN's. LLNL has extensively studied an ANSI standard protocol, Fibre Channel (FC), and

implemented an experimental space division multiplexed Local Area Network (LAN). The prototype development/demonstration LAN was sponsored by LLNL's Defense Systems Program.

C. Fibre Channel is endorsed by disk manufacturing, workstation, and the large computer systems communities. It delivers variable sized packets with an emphasis on very large files. While it is possible to have highly loaded channels in an FC LAN, the technology emphasis is to achieve reliable low latency and very high bandwidth transmissions on demand. FC has the potential to deliver all desired LAN services. Existing application requirements are met at 10 to 100 times current rates using unmodified application codes and existing network upper level protocols based on IP. Further, FC is designed to transparently transport the standard "data storage" protocols, HIPPI, IPI-3, and SCSI. Upper level protocols will evolve to conveniently and economically intermix voice, video, data, real-time, and interactive traffic.

D. The telecommunications industry has proposed to transmit all information using fixed size (fifty-three-byte) packets or cells using a technology known as Asynchronous Transfer Method (ATM). ATM can potentially simplify the task of applying statistical multiplexing techniques in balancing varying traffic demands to fully utilize their communications channels. The very small cell size makes it convenient to mix independent, and hopefully complementary, mixtures of voice, video, fax, and data traffic. ATM also has the potential to carry all desired services. A major issue is whether high performance computer traffic has characteristics that will invalidate the statistical assumptions of most ATM implementations, thus leading to unacceptable latency and data loss.

C. Description

The Gigabit Networking Technology project was composed of four independent but complementary CRADA efforts which sought to develop, test, and evaluate alternate approaches to interconnecting gigabit LANs and WANs. The goal of the Gigabit Networking Technology project was to test, demonstrate, and evaluate some of the most promising components of cutting-edge telecommunication technologies that will directly support defense and energy applications, as well as many commercial and scientific interests. LLNL, other participating laboratories, DOE, and the nation will benefit greatly from this CRADA because it has helped focus attention on interconnected gigabit LANs and WANs — the technology infrastructure that will make possible the "information super-highway."

LLNL's specific project goals were the following (in priority order):

- Investigate Fibre Channel LAN/WAN routing, i.e. "internetworking"
- Investigate Fibre Channel LAN inter-connections over ATM and SONET communication systems
- Promote Driving Applications
  - Scientific collaborations
  - Scientific visualization
  - Teleconferencing
- Collaborate with other XUNET participants to test the technical issues posed by LAN/WAN interconnections and internetworking.

D. Expected Economic Impact

The economic impact of this CRADA is both broad and diffuse. This CRADA's primary focus was on study and demonstration of competing LAN/WAN technologies rather than new product

development. The purpose of this kind of project was to learn the strengths and shortcomings of proposed technologies prior to the commitment of significant product development funding.

The US telecommunications infrastructure is currently undergoing rapid change in both technology and regulatory environment. This change will ultimately result in Broadband Integrated Switched Digital Networks (BISDN) carrying the telecommunication traffic necessary to support the US economy into the twenty-first century. Although the viability of these digital networks was widely presumed, actual proof-of-concept testing was only then beginning at the start of the project through vehicles such as the five gigabit testbed networks supported by NSF and DARPA. Many technical issues remain to be resolved before computers can communicate via BISDN networks and retain the high throughput obtainable in local area networks. Resolving these issues will benefit the US telecommunications industry by offering a clear technological path and demonstrating the credibility of BISDN to supply high-speed data communications, and will benefit the computer industry by providing the means for high-speed wide area networking in a standards-based infrastructure.

E. Benefits to DOE

As the focus of the DOE weapons-related programs evolves from production 'stockpile stewardship', the need for efficient, flexible, computer-integrated design, simulation, and limited manufacturing capability will become critical. The development of successful high-speed local, metropolitan, and wide area networks capable of linking the various DOE sites will be at the heart of such capability. In addition, as even more emphasis is placed on simulation, the ability of high-speed networks to allow the use of massively parallel and vector super computers , storage servers, and workstations -- potentially at widely separated DOE locations -- to address a single problem will be of increasing importance as expensive resources are centralized at a few sites rather than duplicated everywhere.

F. Industry Area

Telecommunications, Data Communications and Information Processing are the broad industrial areas which benefit from this project. This project sought to extend current practices by focusing on ATM and Fibre Channel technologies.

G. LLNL Point of Contact for Project Information

William J. Lennon
Principal Investigator
Lawrence Livermore National Laboratory
Advanced Telecomunications Program
Mail Stop L-541
7000 East Avenue
Livermore, CA 94550
Tel (510) 422-1091
Fax (510) 424-2707

H. Company Size and Point(s) of Contact

Shown below is a table containing publicly available financial information on AT&T. The number of AT&T employees is given in the last row of the table.

AT&T Financial Information

Dollars in millions (except per share amounts)	1995*	1994	1993*	1992	1991*
Results of Operations					
Total revenues	$79,609	$75,094	$69,351	$66,647	$64,455
Net Income (loss)	$139	$4,710	($5,906)	$3,442	$171
Earnings (loss) per common share	$0.09	$3.01	($3.82)	$2.27	$12.00
Dividends declared per common share	$1.32	$1.32	$1.32	$1.32	$1.32
Assets and Capital					
Total assets	$88,884	$79,262	$69,393	$66,104	$62,071
Common shareowners' equity	$17,274	$17,921	$13,374	$20,313	$17,973
Net capital expenditures	$5,997	$4,853	$4,296	$4,328	$4,376
Other Information					
Return on average common equity	0.7%	29.5%	(47.1%)	17.6%	0.9%
Stock price per share at year-end	$64.750	$50.250	$52.500	$51.000	$39.125
Employees	299,300	304,500	317,700	319,000	322,300

* 1995 data reflect a $7.8 billion of pretax business restructuring and other charges.
* 1993 data reflect a $9.6 billion net charge for three accounting changes.
* 1991 data reflect $4.5 billion of business restructuring and other charges.

AT&T point of contact for this project is:

Norman L. Schryer
AT&T Bell Labs
Computing Mathematics Research
Murray Hill, NJ 07974
Phone (908) 582-2912

I. Project Examples

Due to the nature of this CRADA it is difficult to provide tangible 'things' or demonstrations which can be used in "show and tell" situations. Demonstrations involving Fibre Channel and ATM are complex and involve considerable resources to set up. Significant accomplishments which can be cited are:

- LLNL and SNL installed the DS3 link and XUNET switch in LLNL's Building 256.
- Vice President Al Gore observed from AT&T Murray Hill a visualization of a vector field produced here in Livermore and transmitted over the XUNET ATM network.
- LLNL personnel implemented the IP wide area routing policy on the XUNET ATM network.

- LLNL implemented a novel 622 megabit link between LLNL and the U.C. Berkeley XUNET switch. This effort took advantage of a joint LLNL/Pacific Bell project to implement an experimental wave-length division multiplexed (WDM) communication link. The experiment uses optical fiber optic lasers and WDM technology to implement 4 high speed communication channels on a single optical fiber. The first active channel was the XUNET 622 Mbs circuit.
- A small Fibre Channel demonstration LAN was implemented.
- Two LLNL scientists had workstations attached to the local XUNET FDDI ring to facilitate high speed collaborations with colleagues at AT&T Murray Hill and at U.C. Berkeley.
- FC channel bridging over ATM WAN networks was studied in a conceptual design.
- FC transport over SONET was studied in a conceptual design.

J. Release of Information

William J. Lennon
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Tel (510) 422-1091
Fax (510) 424-2707

RELEASE OF INFORMATION

I have reviewed the attached Project Accomplishment Summary prepared by Lawrence Livermore National Laboratory and agree that the information about our CRADA may be released for external distribution.

Norman L. Schryer

12/2/97

Norman L. Schryer
AT&T Bell Labs
Computing Mathematics Research
Murry Hill, NJ 07974

Date

RELEASE OF INFORMATION

I certify that all information contained in this report is accurate and releasable to the best of my knowledge.

Karena McKinley, Director
Industrial Partnerships
and Commercialization

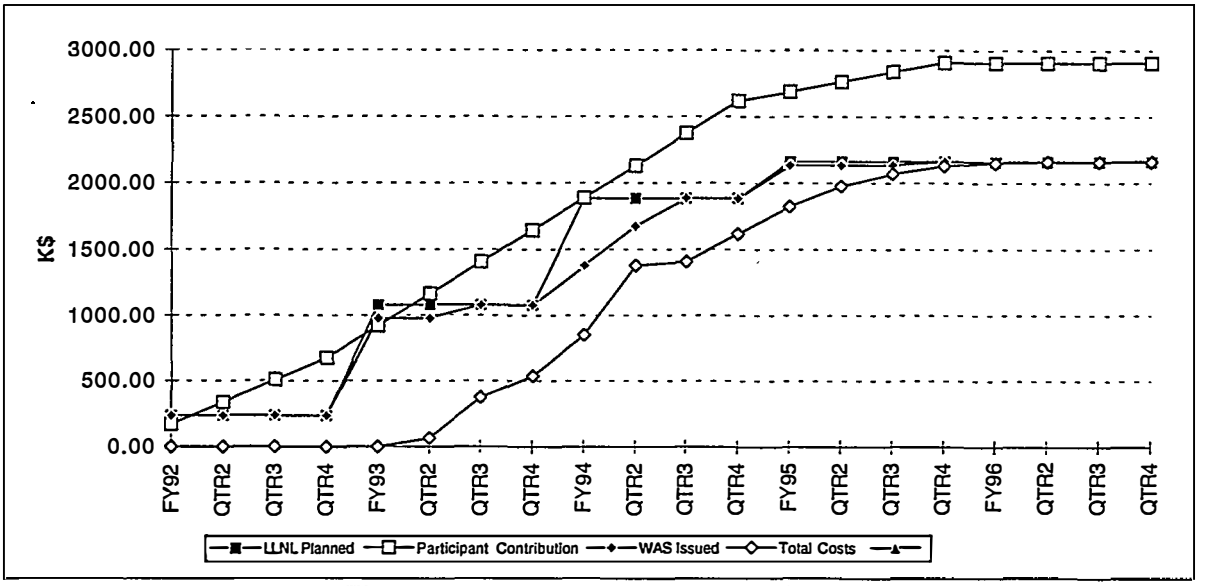
2/18/97
Date

Lawrence Livermore National Laboratory
Final Quarterly Report (Attachment III)

Title:	Gigabit Network	Reporting Period:	07/01/95 - 09/30/96
Participant:	AT&T Bell Laboratory	Date CRADA Executed:	12/01/92
DOE TTI No.:	92-MULT-020-B2	DOE Approval Date:	11/04/92
CRADA No.:	TC-0299-92	Scheduled Ending Date:	12/01/95
TACT:	CA&A	Project Completion Date:	09/30/96
Account Numbers	4725-01, 7606-02	B & R Code (S):	DP030101
Date Accounts Closed: 9/30/96			35DP0301

Approved Funding Profile ($K)

	FY92	FY93	FY94	FY95	FY96	Total
LLNL Planned	237	841	807	280	0	2165
Participant In-Kind	679	969	969	291	0	2908
Participant Funds-In	0	0	0	0	0	0
WAS DP030101	237	738	807	280	10	2072
WAS 35DP0301	0	103	0	0	0	103
Total Costs	0	539	1084	511	31	2165



DP030101	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	FYTD	2062
FY92	0	0	0	0	0	0	0	0	0	0	0	0	0	
FY93	0	0	0	0	13	53	80	75	151	71	35	56	533	
FY94	80	119	104	120	218	171	-118	60	40	79	64	64	1000	
FY95	59	67	64	43	52	56	44	19	30	19	-34	80	499	
FY96	8	7	5	3	1	7	1	0	0	0	0	0	31	

35DP0301	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	FYTD	103
FY92	0	0	0	0	0	0	0	0	0	0	0	0	0	
FY93	0	0	0	0	0	0	0	0	6	0	0	0	6	
FY94	0	5	2	0	22	0	47	0	0	0	-25	32	84	
FY95	0	12	2	0	0	0	0	0	0	0	0	-1	12	
FY96	0	0	0	0	0	0	0	0	0	0	0	0	0	

STAFF w/phone: Lab PI: Bill Lennon (510) 422-1091 Participant: Norman L. Schryer (908) 582-2912

Lab Co-PI: Gary Armstrong (510) 422-7013

DOE OAK: Jerry Scheinberg (510) 637-1653 DOE HQ: A. Larzelere (202) 586-1101

Milestones and Deliverables:

List the complete set of milestones for all phases of the CRADA. Continue on a separate page if necessary.
Report any changes from the original CRADA or previous quarterly report on the CRADA Change Form.

	Completion Date: Scheduled	Actual
1. Develop Fibre Channel Adapters		
1.a) Fibre Channel to SONET Adapter	3/93	Q4 95
1.b) Fiber Channel to ATM Adapter	8/93	Q3 95
1.c) Fabricate "production" adapters	(optional)	(optional)
2. Identify and implement scalable test applications		
2.a) Foster WAN Collaborations	3/93	Q2 92 ff.
2.b) FC LAN	3/93	Q2 95 ff.
2.c) AT&T will operate the XUNET network.	10/92 ff.	Q1 92 ff.
2.d) LLNL will install an XUNET node.	3/93	Completed Q2 93
2.e) LLNL will collaborate with others on collaborative work environments.	3/93 ff.	2/93 ff.
2.f) LLNL will work with other Nat. Labs to identify inter-site collaborations.	8/93 ff.	Q4 94 ff.
3. LLNL will design ATM transport architecture for all known Level 4 Fibre Channel Protocols. (i.e. IP protocol).	6/93 - 6/94	Q2 95 ff.
4. Comparison of Inter-LAN transport mechanisms		
4.a) LLNL will test applications using Fibre Channel	2/93	Q1 95 ff.
4.b) LLNL will test applications using Fibre Channel over SONET.	5/93 ff.	Q4 95 ff.
4.c) LLNL will pursue borrowing fiber at other Gbs WAN sites to continue Fibre Channel over SONET.	11/93 ff.	Completed Q4 94
4.d) LLNL will test applications over XUNET using the FC/ATM adapter.	8/93 ff.	Q3 95

Note: "ff." is an abbreviation for "going forward from this date"

Verification of participants' in-kind contribution was made in accordance with LLNL policy. Explain basis of verification: Please initial: YES X NO

We observde that the network was operational and AT&T provided help in solving problems. AT&T's in-kind contributions were to support the XUNET infrastructure at universities and routing hubs. AT&T met their commitment.

List any subject inventions by either party (include IL# for LLNL inventions), additional background intellectual property, patents applied for, software copyrights, publications, awards, licenses granted or reportable economic impacts

Verification that all equipment and proprietary information has been returned to the initial owner or permanently transferred Please initial: YES X NO

Accomplishments

Describe Technical/Non-Technical lessons learned and other observations.
Summarize causes/justification of deviations from original scope of work.

See Final Report

Reporting Period: 07/01/95 - 09/30/96
DOE TTI No.: 92-MULT-020-B2
CRADA No.: TC-0299-92

Reviewed by CRADA project Program Manager: _____ Date: _____

Reviewed by Karena McKinley, Acting Director, LLNL IP&C: _____ Date: _____

Direct questions regarding this Report to IP&C Resource Manager, Susan Springer, at (510) 422-5507