Armando L. Caro, Jr.

me@armandocaro.net
www.armandocaro.net

Education

Ph.D. in Computer and Information Sciences **August 2005**
University of Delaware
Advisor: Prof. Paul D. Amer
D**issertation:** *End-to-End Fault Tolerance Using Transport Layer Multihoming*

M.S. in Computer and Information Sciences **May 2000**
University of Delaware

B.S. with Distinction in Computer and Information Sciences **May 1998**
University of Delaware
T**hesis:** *ReMDoR 2.0: Remote Multimedia Document Retrieval Over Partially-Ordered, Partially-Reliable Transport Protocols*

Experience

BBN Technologies **Cambridge, Massachusetts, USA**
Network Scientist **September 2005 - Present**

Adaptive Distributed Radio Open-source Intelligent Network (ADROIT)

We are building an open-source platform that combines software-defined radios, modular network components, and cognitive algorithms to allow wireless networks to dynamically adapt in real-time to environmental conditions.

Specialized Network Design and Analysis

We are consulting with a customer to design a network to meet their specialized communication needs. *Further details are proprietary.*

Protocol Engineering Lab (PEL), University of Delaware **Newark, Delaware, USA**
Graduate Research Assistant **June 1998 - May 2005**

End-to-End Fault Tolerance Using Transport Layer Multihoming

My dissertation investigated transport layer techniques that improve end-to-end fault tolerance and throughput. Often, access links (for both clients and servers) are a single point of failure for end-to-end reachability. Routing protocols (in particular, BGP) may also take a significant amount of time (often tens of minutes) to converge on a new route when a link failure is detected. Multihoming support at the transport layer addresses both types of failures by allowing a transport layer session to bind multiple IP addresses at each endpoint. This feature provides both endpoints with multiple paths with which to communicate, and thus the ability to failover to an alternate path when a path failure occurs.

I investigated multihoming retransmission policies and failover thresholds with the Stream Control Transmission Protocol (SCTP). I demonstrated that SCTP's retransmission policy in RFC2960 often degrades performance in non-failure scenarios by sending all retransmissions to an alternate

path. Via ns-2 simulations, I showed that the best performance for failure and non-failure scenarios is provided by a policy which sends fast retransmissions to the primary path and timeout retransmissions to an alternate path. This new policy has been implemented in the BSD KAME stack, and has IETF approval to be included in RFC2960-bis.

To further improve SCTP's performance, I developed the Multiple Fast Retransmit (MFR) algorithm to reduce the number of timeouts. MFR, which can be applied to both TCP and SCTP, maintains extra state at the sender to allow a lost fast retransmission to be fast retransmitted again instead of incurring a timeout. MFR has been implemented in the BSD KAME implementation of SCTP.

I demonstrated that aggressive failover thresholds often trigger spurious failovers, but I also found, unexpectedly, that spurious failovers do not degrade performance. Even when spurious failovers occur onto an alternate path with a higher loss rate and/or larger delay, the goodput is never worse and is often better due the temporal nature of failovers. However, I argue that calling this behavior *failover* is misleading. The vast majority of single timeouts are not caused by failure conditions. I argue that two thresholds should be used. The first threshold aggressively migrates traffic temporarily to an alternate path on a single timeout. The second threshold, on the other hand, is more conservative to accurately detect failure.

SCTP Utilities

I am the principle developer of the SCTP module for the ns-2 network simulator. This SCTP implementation supports the major features of SCTP including multistreaming, multihoming, failover, ordered & unordered service, and the partial reliability service extension (RFC3758). Initially the module was available only as a patch, but has since been merged with the main ns-2 distribution (as of ns-2.27).

With Gerard Heinz and John Fiore, I co-developed the SCTP module for tcpdump – the de-facto standard for packet sniffing software. The SCTP decoder module is now included in tcpdump versions 3.7 and greater.

NETCICATS for the Web

NETCICATS is a Network-Conscious Image Compression And Transmission System developed in UD's PEL lab. Traditional image compression techniques seek the smallest possible size for a given level of image quality. To contrast, network-conscious image compression techniques take into account the fact that a compressed image will be transmitted over a network that may lose and reorder packets. The data is segmented into path MTU-size data units, each of which can be independently decompressed and displayed on its own. Under lossy network conditions, a network-conscious image transmitted with an unordered transport service permits faster progressive display at the receiver than a traditional image transmitted over an ordered transport service. This advantage comes in exchange for a small penalty in overall compression. This research demonstrated (1) the value of considering network characteristics in designing image formats, and (2) the value of unordered transport service.

I ported much of NETCICATS to a web environment. I developed a Netscape plugin that would fetch network-conscious images using our lab's Universal Transport Library (UTL) and display the images in the browser. UTL allows an application to use a common API for a variety of experimental transport protocols developed in our lab.

Nokia Research Center **Helsinki, Finland**
Research Intern **Summer 2001**

Initial SCTP Simulation Investigation

With Janardhan Iyengar, I completed the first two releases of the ns-2 SCTP module, which supported single-homed associations and the partial-reliability (PR-SCTP) extension (known then as the unreliable data mode extension). PR-SCTP allows an SCTP sender to assign different levels of reliability to data so that lost data may be controllably retransmitted only until the reliability threshold for that data is reached. If the reliability threshold is reached for unacked data, the sender abandons that data and notifies the receiver (with Forward TSNs) to do the same.

Using ns-2, I evaluated SCTP's congestion control algorithms for protocol correctness (with Sack TCP as a guide), and my tests concluded that the algorithms operated properly. I also studied PR-SCTP for correctness and efficiency, and found a few problems with the specification. The first problem was that the congestion window was being incorrectly credited for data that was abandoned. The second problem was that a single loss event could generate many Forward TSNs, which adds overhead and possibly contributes to congestion. The third problem was that the Forward TSNs did not include stream information, and thus often caused ambiguity at the receiver. This ambiguity restricted the receiver from actually abandoning data and caused head-of-line blocking between streams – defeating the purpose of SCTP's multistreaming feature. I worked with the PR-SCTP authors to correct the specification.

Telcordia Technologies **Morristown, New Jersey, USA**
Research Intern **Summer 2000**

ITSUMO QoS

The Internet Technologies Supporting Universal Mobile Operations (ITSUMO) project is a collaboration between Telcordia Technologies and Toshiba Research formed in February 1999 to develop IP-centric access systems integrating voice, data, and multimedia services for mobile devices. With Jyh-Cheng Chen, I designed the dynamic service level agreement/specification negotiation protocol and the diffserv-based QoS architecture. I implemented a complete prototype of the architecture on 4 mobile laptop hosts and 3 desktops (domain access servers) running Linux. I demonstrated that the mobile hosts could roam freely between the 3 domains while transmitting and receiving video and voice at the negotiated QoS. Each handoff into a new domain required a new IP address using the Dynamic Registration and Configuration Protocol (DRCP), secure client-network registration using the Basic User Registration Protocol (BURP), and finally QoS negotiation and enforcement using our architecture.

Telcordia Technologies **Morristown, New Jersey, USA**
Research Intern **Summer 1999**

ITSUMO Secure Registration

I evaluated several proposals for adding secure registration to a Mobile IP infrastructure, and selected the most appropriate proposal for the ITSUMO architecture. I also extended DHCP to incorporate the same secure registration mechanism. To demonstrate the security functionality, I integrated the security mechanism into an open source implementation of Mobile IP and DHCP. Setting up and experimenting with a Mobile IP testbed helped identify some shortcomings of DHCP for ITSUMO's requirements. Since DHCP was designed for hosts on a fixed LAN and

not for roaming hosts, DHCP does not efficiently use scarce wireless bandwidth or provide a link layer independent mechanism for notifying a client that a new address request is needed. These inadequacies of DHCP partially motivated the design of the Dynamic Registration and Configuration Protocol (DRCP).

Protocol Engineering Lab, University of Delaware **Newark, Delaware, USA**
Undergraduate Research Assistant **June 1996 - June 1998**

ReMDoR

With Phillip Conrad, I developed an interactive Remote Multimedia Document Retrieval (ReMDoR) system. ReMDoR's architecture resembles the web in that a browser retrieves documents from a server. However, unlike web documents, ReMDoR documents have a time dimension requiring synchronization of audio, still images, graphics, text, pauses, and interactions. The motivation for ReMDoR was to demonstrate the practical benefits of using a partially ordered and partially reliable transport service for multimedia communications. ReMDoR interfaced with our lab's Universal Transport Library (UTL) to dynamically choose among several experimental transport protocols. We designed a specification language for creating multimedia presentations. Using Lex & Yacc, I developed a parser for converting the specification offline into a file format we designed for real-time efficiency. We also designed a transfer syntax that the server used to transmit application data to the fetching browser. The browser was developed in a UNIX environment using the X/Xt/Motif graphics libraries, and I implemented a Network-Conscious GIF image decoder for the browser.

Journal Publications

1. A. Caro, P. Amer, R. Stewart. Retransmission Policies for Multihomed Transport Protocols. *Computer Communications*. (to appear)
2. A. Caro, P. Amer, R. Stewart. Rethinking End-to-End Failover with Transport Layer Multihoming. *Annals of Telecommunications*, 61(1-2), January-February 2006.
3. A. Caro, J. Iyengar, P. Amer, S. Ladha, G. Heinz, K. Shah. SCTP: A Proposed Standard for Robust Internet Data Transport. *IEEE Computer*, 36(11):56-63, November 2003.
4. P. Amer, S. Iren, G. Sezen, P. Conrad, M. Taube, A. Caro. Network-Conscious GIF Image Transmission over Internet. *Computer Networks*, 31(7):693-708, April 1999.

Conference Publications

1. A. Caro, P. Amer, R. Stewart. Retransmission Schemes for End-to-End Failover with Transport Layer Multihoming. *IEEE Global Telecommunications Conference (GLOBECOM)*, Dallas, TX, November 2004.
2. S. Ladha, P. Amer, A. Caro, J. Iyengar. On the Prevalence and Evaluation of Recent TCP Enhancements. *IEEE Global Telecommunications Conference (GLOBECOM)*, Dallas, TX, November 2004.
3. A. Caro, P. Amer, R. Stewart. End-to-End Failover Thresholds for Transport Layer Multihoming. *IEEE Military Communications Conference (MILCOM)*, Monterey, CA, November 2004.

4. A. Caro, P. Amer, R. Stewart. Transport Layer Multihoming for Fault Tolerance in FCS Networks. *IEEE Military Communications Conference (MILCOM)*, Boston, MA, October 2003.
5. S. Ladha, P. Amer, A. Caro. On The Evaluation of Transport Protocols for FCS Networks. *IEEE Military Communications Conference (MILCOM)*, Boston, MA, October 2003.
6. A. Caro, P. Amer, J. Iyengar, R. Stewart. Retransmission Policies with Transport Layer Multihoming. *IEEE International Conference on Networking (ICON)*, Sydney, Australia, September 2003.
7. J. Iyengar, A. Caro, P. Amer, G. Heinz, R. Stewart. Making SCTP More Robust to Changeover. *International Symposium on Performance Evaluation of Computer and Telecommunication Systems (SPECTS)*, Montreal, Canada, July 2003.
8. P. Conrad, A. Caro, P. Amer. ReMDoR: Remote Multimedia Document Retrieval over Partial Order Transport. *ACM Multimedia*, Ottawa, Canada, September 2001.
9. P. Conrad, G. Heinz, A. Caro, P. Amer, J. Fiore. SCTP in Battlefield Networks. *IEEE Military Communications Conference (MILCOM)*, Washington, DC, October 2001.
10. J.C. Chen, A. Caro, A. McAuley, S. Baba, Y. Ohba, P. Ramanathan. A QoS Architecture for Future Wireless IP Networks. *IASTED International Conference on Parallel and Distributed Computing and Systems (PDCS) 2000*, Las Vegas, NV, November 2000.
11. S. Iren, P. Amer, A. Caro, P. Conrad, G. Sezen, M. Taube. Network- Conscious Compressed Image Transmission over Battlefield Networks. *IEEE Military Communications Conference (MILCOM)*, Boston, October 1998.
12. P. Conrad, P. Amer, M. Taube, G. Sezen, S. Iren, A. Caro. Testing Environment for Innovative Transport Protocols. *IEEE Military Communications Conference (MILCOM)*, Boston, October 1998.
13. P. Amer, S. Iren, G. Sezen, P. Conrad, M. Taube, A. Caro. Network-Conscious GIF Image Transmission over Internet. *International Workshop on High Performance Protocol Architectures (HIPPARCH)*, London, June 1998.
14. P. Conrad, P. Amer, E. Golden, S. Iren, R. Marasli, A. Caro. Transport QoS over Unreliable Networks: No Guarantees, No Free Lunch! *IFIP International Workshop on Quality of Service (IWQOS)*, New York, NY, May 1997.

Conference Posters

1. A. Caro, J. Iyengar, P. Amer, G. Heinz, R. Stewart. Using SCTP Multihoming for Fault Tolerance and Load Balancing. Poster in *ACM SIGCOMM 2002*, Pittsburgh, PA, August 2002. Abstract in *ACM Computer Communication Review*, 32(3):23, July 2002.

IETF Drafts

1. R. Stewart, I. Arias-Rodriguez, K. Poon, A. Caro, M. Tuexen. Stream Control Transmission Protocol (SCTP) Specification Errata and Issues. <draft-ietf-tsvwg-sctpimpguide-15.txt>, September 2005. (work in progress)
2. J. Chen, A. McAuley, A. Caro, S. Baba, Y. Ohba, P. Ramanathan. QoS Architecture Based on Differentiated Services for Next Generation Wireless IP Networks. <draft-itsumo-wireless-diffserv-00.txt>, July 2000. (expired)

Conference Talks

1. Retransmission Schemes for End-to-End Failover with Transport Layer Multihoming. *IEEE Global Telecommunications Conference (GLOBECOM)*, Dallas, TX, November 2004.
2. On the Prevalence and Evaluation of Recent TCP Enhancements. *IEEE Global Telecommunications Conference (GLOBECOM)*, Dallas, TX, November 2004.
3. End-to-End Failover Thresholds for Transport Layer Multihoming. *IEEE Military Communications Conference (MILCOM)*, Monterey, CA, November 2004.
4. Concurrent Multipath Transfer Using Transport Layer Multihoming: Performance Under Varying Bandwidth Proportions. *IEEE Military Communications Conference (MILCOM)*, Monterey, CA, November 2004.
5. Transport Layer Multihoming for Fault Tolerance in FCS Networks. *IEEE Military Communications Conference (MILCOM)*, Boston, MA, October 2003.
6. Retransmission Policies with Transport Layer Multihoming. *IEEE International Conference on Networking (ICON)*, Sydney, Australia, September 2003.

Invited Talks / Seminars

1. Retransmission Policies for End-to-End Failover with Transport Layer Multihoming. Nokia Research Center. Mountain View, CA, January 7, 2005.
2. SCTP Research. Cisco Systems. San Jose, CA, October 8, 2003.
3. Resilient Overlay Networks. SIGNET, CIS Dept, University of Delaware, October 2, 2002.

Public-domain Software

1. A. Caro and J. Iyengar. SCTP module for ns-2. http://pel.cis.udel.edu
2. G. Heinz, J. Fiore, A. Caro. SCTP module for tcpdump. http://www.tcpdump.org
3. A. Caro. webAlbum (generates a web-based photo & video album). http://www.armandocaro.net

Professional Service

- TPC Member, Workshop on NS-2, 2006
- Reviewer, INFOCOM 2005
- Reviewer, INCP 2005
- Reviewer, CoNext 2005
- Reviewer, ISCC 2005
- Reviewer, *IEEE Communication Letters*, 2003 - 2005
- Reviewer, IDMS/PROMS 2002

Honors

The Coalition to Diversify Computing Award **2004**
$1K travel grant for GLOBECOM 2004, Dallas, Texas

University of Delaware Dissertation Fellowship **2004 - 2005**
Full tuition & $14K stipend for a single school year
10 PhD students awarded from a population of 1200 PhD students

University of Delaware Presidential Fellowship **1999 - 2004**
Full tuition & $14K stipend for a single school year
2 students nominated from each graduate department
Received 5 times (not renewable; each year is a separate competition)

University of Delaware Alumni Enrichment Award **2003**
$2K travel grant for ICON 2003, Sydney, Australia

Hatem M. Khalil Memorial Award **1998**
Outstanding achievement in software engineering (for ReMDoR)
One CIS major selected from CIS Dept each year

John P. Hyatt Scholarship **1997 - 1998**
3.0+ GPA

Hispanic Students of Distinction **1995 - 1998**
3.0+ GPA
Received 4 times

Delaware Governor's Scholars Award Scholarship **1996**
Outstanding academics

University Academic Award **1996**
Outstanding academics

Affiliations

- ACM (Association for Computing Machinery)
- IEEE (Institute of Electrical and Electronics Engineers)

Citizenship

U.S. Citizen

Languages

English, Spanish