Network Time Synchronization Research Project

Table of Contents

Projects


Autonomous Networks


NTP Project

Documenation


The Network Time Protocol (NTP) Distribution


Computer Network Time Synchronization (book)

NTP Tutorial

How NTP Works

NTP White Papers


Executive Summary: Computer Network Time Synchronization


The NTP Timescale and Leap Seconds


NTP Timestamp Calculations


Maya glyph *alautun*

Researchers involved: David Mills, graduate students and many volunteers

Funding: Defense Advanced Research Projects Agency (DARPA), National Science Foundation (NSF), Navy Surface Weapons Center (NSWC) and Jet Propulsion Laboratory/NASA

Last update: 13-May-2012 17:14 UTC

Briefing Slides

Note: The recommended format is PDF and Adobe Acrobat Reader 3 or later. Where available, PowerPoint presentations are provided.

- Network Time Protocol (NTP) General Overview PowerPoint | PDF
- NTP Architecture, Protocol and Algorithms PowerPoint | PDF
- NTP Procedure Descriptions and Flow Diagrams PowerPoint | PDF
- NTP Clock Discipline Principles PowerPoint | PDF
- NTP Security Model PowerPoint | PDF
- NTP Security Algorithms PowerPoint | PDF
- NTP Security Protocol PowerPoint | PDF
- NTP Precision Synchronization PowerPoint | PDF
- NTP Performance Analysis PowerPoint | PDF
- NTP Algorithm Analysis PowerPoint | PDF
- NTP Interleaved Protocol for LANs and Space Data Links PowerPoint | PDF
- Long-Range Dependency Effects in NTP Timekeeping PowerPoint | PDF
- Mainframe Timekeeping with the IBM 9037 Sysplex PowerPoint | PDF

Importance of the Problem

/The Network Time Protocol (NTP) is widely used in the Internet to synchronize computer clocks to national standard time. The NTP architecture, protocol and algorithms have evolved over


The NTP Era and Era Numbering


Timestamp Capture Principles


Analysis and Simulation of the NTP On-Wire Protocols


Time Synchronization for Space Data Links


NTP Security Analysis


IEEE 1588 Precision Time Protocol (PTP)

more than three decades to the NTP Version 4 specification and reference implementations for Unix, VMS and Windows.

NTP time synchronization services are widely available in the public Internet, which today includes several thousand servers in most countries and on every continent of the globe, including Antarctica, and sometimes in space, on ships and on the sea floor. These servers support a total population estimated at over 25 million computers in the global Internet.

Previous funded research has resulted in a series of improvements in accuracy and reliability of the protocol and supporting algorithms. Used in the Internet of today with computers ranging from personal workstations to supercomputers, NTP provides accuracies generally in the range of 0.1 ms with fast LANs and computers and up to a few tens of milliseconds in the intercontinental Internet.

The current NTP Version 4 speculation RFC-5905 and reference implementation represent a significant enhancement to the NTP Version 3 specification and implementation first developed in 1992. Specifically, these involve provisions for an autonomous configuration and autonomous authentication capability which provides for automatic server discovery and secure server authentication using both symmetric key and public key cryptography described in RFC-5906.

Brief Description of Work and Results

We consider the NTP project and ongoing development a basically mature project, although there is always the opportunity for incremental advances. The NTP documentation and NTP white papers linked from this page provide a current status report, while links to the software distribution, documentation and discussion groups are at the Network Time Protocol web site.

There have been significant changes and additions to the NTPv4 protocol specification RFC-5905 and the Autokey specification RFC-5906 since their publication in 2010. In addition, there have been significant unreporded changes since the original drafts were written in 2006. The five-year delay in the IETF publishing process has meant that these changes have not kept pace with the current development and there are no current plans to update the documents in the near future.

However, there is a considerable body of progress reported in the online documentation NTP Version 4 Release Notes and the white

papers Analysis and Simulation of the NTP On-Wire Protocols and NTP Security Analysis. These documents should be reformatted as an Informational RFC and relevant sections should be incorporated in a RFC-5905 replacement or supplement. While the book cited below cites some of the improvements, the most recent are documented only in the online documentation and white papers.

Future Plans

We anticipate future development of time synchronization technology for planetary networks and deep space missions, as described in the white paper Time Synchronization for Space Data Links. We expect to continue the study of interoperability between NTP and the IEEE 1588 Precision Time Protocol. These issues are discussed in a new book [1]. We plan to incorporate certain minor enhancements to improve error recovery in the reference implementation, as described in the white paper Analysis and Simulation of the NTP On-Wire Protocols.

We expect to refine the NTP Autokey protocol and incorporate refinements suggested in the white paper NTP Security Analysis. We expect to continue the testing and verification program with UTC leap seconds, as described in the white paper The NTP Timescale and Leap Seconds and to verify correct operation in case of era rollover, as described in the white paper NTP Timescale Calculations.

We expect to further refine the Manycast model to improve stability in networks with large numbers of servers and clients. The means proposed to do this involve a whisper campaign where Manycast servers keep track of dependent clients by means of specific Autokey messages. The servers would then run load balancing and stratum selection algorithms suggested in a recent dissertation.

Selected Publications

1. Mills, D.L. Network Time Synchronization - the Network Time Protocol on Earth and in Space. CRC Press, 2011, 466 pp.
2. Mills, D., J. Martin (Ed.), et al. Network Time Protocol Version 4: protocol and algorithm specification. Request for Comments RFC 5905, Internet Engineering Task Force, June, 2010. ASCII
3. Mills, D., B. Haberman (Ed.). Network Time Protocol Version 4: Autokey specification. Request for Comments RFC 5906,

Internet Engineering Task Force, June, 2010. ASCII
4. Mills, D.L. Network Time Protocol Version 4 reference and implementation guide. Electrical and Computer Engineering Technical Report 06-06-1, University of Delaware, June 2006, 83 pp, PDF
5. Mills, D.L. The Autokey security architecture, protocol and algorithms. Electrical and Computer Engineering Technical Report 06-1-1, University of Delaware, January 2006, 59 pp. PDF
6. Mills, D., D. Plonka and J. Montgomery. Simple network time protocol (SNTP) version 4 for IPv4, IPv6 and OSI. Network Working Group Report RFC-4330, University of Delaware, December 2005, 27 pp. ASCII Major revision and update of: *Ibid*. Network Working Group Report RFC-2030, University of Delaware, October 1996, 20 pp.
7. Mills, D.L., J. Levine, R. Schmidt and D. Plonka. Coping with overload on the Network Time Protocol public servers. *Proc. Precision Time and Time Interval (PTTI) Applications and Planning Meeting* (Washington DC, December 2004), 5-16. Paper: PDF, Slides: PDF | PowerPoint
8. Mills, D.L. The Autokey security architecture, protocol and algorithms. Electrical and Computer Engineering Technical Report 04-4-1, University of Delaware, April 2004, 57 pp. PDF
9. Mills, D.L. A brief history of NTP time: confessions of an Internet timekeeper. *ACM Computer Communications Review 33, 2* (April 2003), 9-22. PDF
10. Levine, J., and D. Mills. Using the Network Time Protocol to transmit International Atomic Time (TAI). *Proc. Precision Time and Time Interval (PTTI) Applications and Planning Meeting* (Reston VA, November 2000). Paper: PDFMinar, N. A survey of the NTP network. MIT Media Laboratory, December 1999, 10 pp. PDF
11. Mills, D.L. Cryptographic authentication for real-time network protocols. In: *AMS DIMACS Series in Discrete Mathematics and Theoretical Computer Science, Vol. 45* (1999), 135-144. Paper: PDF, Slides: PowerPoint
12. Mills, D.L. Adaptive hybrid clock discipline algorithm for the Network Time Protocol. *IEEE/ACM Trans. Networking 6, 5* (October 1998), 505-514. PDF.
13. Mills, D.L., A. Thyagarajan and B.C. Huffman. Internet timekeeping around the globe. *Proc. Precision Time and Time Interval (PTTI) Applications and Planning Meeting* (Long Beach CA, December 1997), 365-371. Paper: PDF Slides: PowerPoint | PDF

14. Sethi, A.S., H. Gao, and D.L. Mills. Management of the Network Time Protocol (NTP) with SNMP. Computer and Information Sciences Report 98-09, University of Delaware, November 1997, 32 pp. PDF
15. Mills, D.L. Clock discipline algorithms for the Network Time Protocol Version 4. Electrical Engineering Report 97-3-3, University of Delaware, March 1997, 35 pp. Abstract: PDF, Body: PDF
16. Mills, D.L. Authentication scheme for distributed, ubiquitous, real-time protocols. *Proc. Advanced Telecommunications/Information Distribution Research Program (ATIRP) Conference* (College Park MD, January 1997), 293-298. Paper: PDF Slides: PowerPoint | PDF
17. Mills, D.L. The network computer as precision timekeeper. *Proc. Precision Time and Time Interval (PTTI) Applications and Planning Meeting* (Reston VA, December 1996), 96-108. Paper: PDF Slides: PowerPoint | PDF.
18. Mills, D.L. Proposed authentication enhancements for the Network Time Protocol version 4. Electrical Engineering Report 96-10-3, University of Delaware, October 1996, 36 pp. Abstract: PDF, Body: PDF
19. Mills, D.L. Simple network time protocol (SNTP) version 4 for IPv4, IPv6 and OSI. Network Working Group Report RFC-2030, University of Delaware, October 1996, 18 pp. ASCII Major revision and update of: *Ibid*. Network Working Group Report RFC-1769, University of Delaware, March 1995, 14 pp. ASCII Also published (with figures) as *Ibid* Electrical Engineering Department Report 96-10-2, University of Delaware, October 1996, 14 pp. Abstract: PDF, Body: PDF
20. Mills, D.L. Improved algorithms for synchronizing computer network clocks. *IEEE/ACM Trans. Networks 3, 3* (June 1995), 245-254. PDF Revised from: *ibid*. *Proc. ACM SIGCOMM 94 Symposium* (London UK, September 1994), 317-327. PDF
21. Mills, D.L. Simple network time protocol (SNTP) version 4 for IPv4, IPv6 and OSI. Network Working Group Report RFC-2030, University of Delaware, October 1996, 18 pp. ASCII Major revision and update of: *Ibid*. Network Working Group Report RFC-1769, University of Delaware, March 1995, 14 pp. ASCII Also published (with figures) as *Ibid* Electrical Engineering Department Report 96-10-2, University of Delaware, October 1996, 14 pp. Abstract: PDF, Body: PDF
22. Mills, D.L. Proposed authentication enhancements for the Network Time Protocol version 4. Electrical Engineering Report 96-10-3, University of Delaware, October 1996, 36

pp. Abstract: PDF, Body: PDF
23. Mills, D.L, and A. Thyagarajan. Network time protocol version 4 proposed changes. Electrical Engineering Department Report 94-10-2, University of Delaware, October 1994, 32 pp. Abstract: PDF, Body: PDF
24. Mills, D.L. Unix kernel modifications for precision time synchronization. Electrical Engineering Department Report 94-10-1, University of Delaware, October 1994, 24 pp. Abstract: PDF, Body: PDF Major revision and update of: Network Working Group Report RFC-1589, University of Delaware, March 1994. 31 pp. ASCII
25. Mills, D.L. A kernel model for precision timekeeping. Network Working Group Report RFC-1589, University of Delaware, March 1994. 31 pp. ASCII
26. Mills, D.L. Precision synchronization of computer network clocks. Electrical Engineering Department Report 93-11-1, University of Delaware, November 1993, 66 pp. Abstract: PDF, Body: PDF
27. Mills, D.L. Modelling and analysis of computer network clocks. Electrical Engineering Department Report 92-5-2, University of Delaware, May 1992, 29 pp. Abstract: PDF, Body: PDF
28. Mills, D.L. Network Time Protocol (Version 3) specification, implementation and analysis. Network Working Group Report RFC-1305, University of Delaware, March 1992, 113 pp. Abstract: PDF, Body: PDF, Appendices: PDF Revised from: Electrical Engineering Department Report 90-6-1, University of Delaware, June 1990, 103 pp. Abstract: PDF, Body: PDF, Appendices: PDF
29. Mills, D.L. On the chronology and metrology of computer network timescales and their application to the Network Time Protocol. *ACM Computer Communications Review 21, 5* (October 1991), 8-17. PDF
30. Mills, D.L. Internet time synchronization: the Network Time Protocol. *IEEE Trans. Communications COM-39, 10* (October 1991), 1482-1493. PDF Also in: Yang, Z., and T.A. Marsland (Eds.). *Global States and Time in Distributed Systems*. IEEE Computer Society Press, Los Alamitos, CA, 1994, 91-102. Condensed from: *Ibid*. Network Working Group Report RFC-1129, University of Delaware, October 1989. Also published as: Electrical Engineering Department Report 89-9-1, University of Delaware, September 1989.
31. Mills, D.L. On the accuracy and stability of clocks synchronized by the Network Time Protocol in the Internet system. *ACM Computer Communication Review 20, 1*

(January 1990), 65-75. PDF
32. Mills, D.L. Internet time synchronization: the Network Time Protocol. Network Working Group Report RFC-1129, University of Delaware, October 1989, 27 pp. Abstract: PDF, Body: PDF Also published as: Electrical Engineering Department Report 89-9-1, University of Delaware, September 1989.
33. Mills, D.L. Measured performance of the Network Time Protocol in the Internet system. Network Working Group Report RFC-1128. University of Delaware, October 1989, 18 pp. Abstract: PDF, Body: PDF Also published as: Electrical Engineering Department Report 89-9-3, University of Delaware, September 1989, 16 pp. Abstract: PDF, Body: PDF
34. Mills, D.L. Network Time Protocol (Version 2) specification and implementation. Network Working Group Report RFC-1119, 61 pp. University ofDelaware, September 1989. Abstract: PDF, Body: PDF Also published as: Electrical Engineering Department Report 89-9-2, University of Delaware, September 1989. Abstract: PDF, Body: PDF
35. Mills, D.L. Network Time Protocol (Version 1) specification and implementation. Network Working Group Report RFC-1059. University of Delaware, July 1988. ASCII. Also published as: Electrical Engineering Department Report 88-4-1, University of Delaware, May 1988.
36. Mills, D.L. A distributed-protocol authentication scheme. Network Working Group Report RFC-1004, University of Delaware, April 1987. ASCII