Electrical Engineering Department University of Delaware
Technical Report 93-11-1 November 1993

Precision Synchronization of Computer Network Clocks

David L. Mills

Abstract

This report builds on previous work involving the Network Time Protocol, which is used to synchronize computer clocks in the Internet. It describes a series of incremental improvements in system hardware and software which result in significantly better accuracy and stability, especially in primary time servers directly synchronized to radio or satellite time services. These include novel interfacing techniques and operating system features. The goal in this effort is to improve the synchronization accuracy for fast computers and networks from the tens of milliseconds regime of the present technology to the submillisecond regime of the future.

In order to assess how well these improvements work, a series of experiments is described in which the error contributions of various modern Unix system hardware and software components are calibrated. These experiments define the accuracy and stability expectations of the computer clock and establish its design parameters with respect to time and frequency error tolerances. The report concludes that submillisecond accuracies are indeed practical, but that further improvements will be possible only through the use of temperature-compensated clock oscillators.

Keywords: disciplined oscillator, computer clock, network time synchronization.

Sponsored by: Advanced Research Projects Agency under NASA Ames Research Center contract NAG 2-638, National Science Foundation grant NCR-93-01002 and U.S. Navy Surface Weapons Center under Northeastern Center for Engineering Education contract A30327-93.

Table of Contents

1. Introduction . . . 1
2. Network Time Protocol . . . 1
2.1. Calculating Offsets, Delays and Error Bounds . . . 3
2.2. The Unix Local Clock Model . . . 5
2.3. The NTP Local Clock Model . . . 7
3. Hardware and Software Interfaces for Precision Timekeeping . . . 9
3.1. Connection via Serial Port . . . 10
3.1.1. The CLK Facility . . . 12
3.1.2. The PPSCLK Facility . . . 13
3.1.3. The PPS Facility . . . 14
3.2. The IRIG Facility . . . 15
4. Unix Kernel Modifications for Precision Timekeeping . . . 17
4.1. Design Principles . . . 18
4.2. Precision Time Resolution . . . 19
4.3. Daemon and Application Interfaces . . . 20
4.4. Leap Seconds . . . 21
5. Timekeeping Errors in Time and Frequency . . . 23
5.1. Clock Reading Errors . . . 24
5.2. Clock Frequency Stability . . . 27
5.2.1. Allan Variance of Typical Workstations . . . 28
5.2.2. PLL Time Constant and Update Interval . . . 30
6. Timekeeping in the Global Internet . . . 31
6.1. Timekeeping in LANs and WANs . . . 32
6.2. NTP System Performance . . . 35
7. Summary and Conclusions . . . 37
8. Acknowledgements . . . 38
9. References . . . 38
Appendix A. Audio IRIG Receiver Programming Information . . . 41
A.1. Application Program Interface . . . 41
A.2. Programming Example . . . 43
A.3. Implementation and Configuration Notes . . . 43
Appendix B. Precision Time Kernel Programming Information . . . 45
B.1. The ntp_gettime() System Call . . . 45
B.2. The ntp_adjtime() System Call . . . 46
B.3. Command/Status Codes . . . 49
B.4. Kernel Variables . . . 49
B.5. Architecture Constants . . . 51
Appendix C. Phase-Lock Loop Simulator . . . 53
Appendix D. DCnet Timekeeping Facilities . . . 59
D.1. Computer and Network Facilities . . . 59
D.2. DCnet Master Clock . . . 60
D.3. Data Collection Facilities . . . 61
D.4. Proof of Performance . . . 64

List of Figures

Figure 1. Subnet Synchronization Topologies . . . 2
Figure 2. Network Time Protocol . . . 2
Figure 3. Measuring Delay and Offset . . . 3
Figure 4. Clock Adjustment Process . . . 6
Figure 5. Update Nomenclature . . . 8
Figure 6. Timing Offsets with Serial ASCII Timecode . . . 10
Figure 7. Timing Offsets with PPS Signal . . . 11
Figure 8. Probability of Error with Ultrix Kernel . . . 20
Figure 9. Kernel Latency for SPARCstation IPC - 1 . . . 24
Figure 10. Kernel Latency for DECstation 5000/240 . . . 25
Figure 11. Kernel Latency for DEC 3000/400 AXP . . . 25
Figure 12. Kernel Latency for SPARCstation IPC - 2 . . . 26
Figure 13. Probability of Error for SPARCstation IPC . . . 27
Figure 14. Typical Clock Oscillator Wander . . . 28
Figure 15. Allan Variance of Typical Local Oscillator . . . 29
Figure 16. Transient Response of NTP PLL - Phase . . . 30
Figure 17. Transient Response of NTP PLL - Frequency . . . 31
Figure 18. Timing Offsets of a Primary Server . . . 32
Figure 19. Timing Offsets Between Primary Servers . . . 32
Figure 20. Timing Offsets of a LAN Secondary Server . . . 33
Figure 21. Timing Offsets of a NSFnet Secondary Server . . . 34
Figure 22. Timing Offsets of a NIST Primary Server . . . 34
Figure 23. Timing Offsets for an Australian Primary Server . . . 35
Figure 24. DCnet Timekeeping Facilities . . . 59
Figure 25. Probability Distribution of GPS Receiver Errors . . . 65
Figure 26. Time Offsets of WWVB Receiver . . . 65
Figure 27. Time Offsets of LORAN-C Receiver . . . 66

List of Tables

Table 1. Table of Leap-Second Insertions . . . 22
Table 2. Characteristics of Typical NTP Peers . . . 36