Practical Limitations of NTP Time Transfer

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***Abstract* - The Network Time Protocol (NTP) is commonly utilized to synchronize computer clocks in packet-switched, wide area networks (WANs) such as the public Internet. The delay asymmetry in WANs, often due to inconsistent routing and/or bandwidth saturation, is usually the dominant source of error. It typically limits NTP time transfer uncertainty to about one millisecond. This paper discusses the uncertainty of NTP time transfer when network asymmetry is largely eliminated. We performed NTP measurements over a local area network (LAN) when both the server and client are referenced to a common clock. Three variations of a LAN are tested, including a direct connection between the server and client with an Ethernet crossover cable. The elimination of network asymmetry reveals other uncertainty sources that serve as practical limitations for NTP time transfer, including client instability, asymmetry in network interface cards, and server instability.**

Key words—local area network, network time protocol (NTP), time transfer

I. Introduction

The Network Time Protocol (NTP) [1, 2] has been utilized for several decades to synchronize computer clocks in packet-switched, variable latency networks. Client software for NTP is built-in to numerous operating systems and Internet devices, and NTP servers around the world now receive many billions of timing requests per day [3].

NTP is typically thought of as a "commodity" source of time, and not as a high accuracy vehicle for time transfer. This is primarily due to the fact that most NTP users utilize the public Internet, typically with the intent of synchronizing their computer clocks to the nearest integer second, an objective that is easily accomplished. Thus, the uncertainties of NTP time transfer are not often studied by time metrologists, and examples of published measurement data provided by timing laboratories are relatively rare. However, a few published studies have recently appeared [4, 5, 6, 7, 8], mostly focusing on the large delay asymmetries of the public Internet, although brief consideration of local area networks (LANs) was provided in [8]. This paper expands upon these earlier studies by focusing entirely on measurements where the delay asymmetry from the network itself has been largely eliminated (through the use of LANs), allowing us to study the other sources of uncertainty that limit NTP performance.

II. Measurement System

The NTP measurements were performed by using a commercially-available NTP server (Symmetricom S350).* Client software developed at the National Institute of Standards and Technology (NIST) was used to initiate the NTP requests and to record the measurements. The server, client, and measurement method are described in the following sections.

A. Description of Server

The NTP server has sufficient bandwidth, according to the manufacturer's specifications, to handle 7 000 requests per second. The server clock was a rubidium oscillator that was disciplined to signals from the Global Positioning System (GPS) satellites via a 12-channel L1 band receiver, with an antenna mounted outdoors on the roof. The accuracy of this clock was measured at NIST and found to be within 100 ns of Coordinated Universal Time (UTC).

The server has four dedicated and isolated Ethernet ports. One port is Gigabit Ethernet (not used in the experiment). The three ports that are used in the experiment are 10/100Base-T connections, capable of transmission of speeds of up to 100 megabits/s. The three ports were configured to automatically negotiate the transmission speed, and were used to connect to three variations of LANs, as discussed in Section III.

B. Description of Client

The client computer's microprocessor was an Intel Quad-Core running at 3.4 GHz.* The client computer had 8 GB of random access memory (RAM) and ran a 64-bit version of the Microsoft Windows 7 operating system (OS).* The client software was referenced to an internal clock board with 0.1 µs (100 ns) resolution. The client clock was continuously synchronized by a 1 pps (pulse per second) output signal from the GPS clock in the server, allowing us to conduct a "common-clock" experiment. The cable connecting the server clock to the client clock had a calibrated (and compensated) delay of 0.017 µs (17 ns), which was smaller than the system's measurement resolution. The client software, previously described in [5], had enough channels to sequentially measure up to 20 NTP servers. For this experiment, three of the available 20 channels were utilized to measure three different LAN configurations, as will be described in Section III.

To reduce the effects of client latency due to system management interrupts (SMIs), the computer's basic input output system (BIOS) was configured to disable some of the power performance settings, including: *SpeedStep*, *Cstates Control,* and *Turboboost*. In addition, the on-motherboard network port was disabled, and all software services not necessary for this experiment were shut down or uninstalled.

Two Intel gigabit-capable PCIe dual-port network interface cards (NICs) were installed in the client computer and used for this experiment.* The NICs were configured as shown in Table I, to help reduce the variation in incoming and outgoing packet delays.

TABLE I. NETWORK INTERFACE CARD CONFIGURATION

Network Card Parameter	Setting
Interrupt Moderation Rate	Minimal
Flow Control	Disabled
Tx/Rx Buffers	512
Jumbo Packet	Disabled
Receive Side Scaling (RSS)	Enabled
Power Management	Disabled
Log Link State	Disabled
Wait for Link	Off
QoS Packet Scheduler	Disabled
Adaptive Interframe Spacing	Disabled
Large Send Offload	Enabled

C. Measurement Method

The client requested a timing packet from the server every 10 s. The request was made by sending a 48-byte packet via the user datagram protocol/Internet protocol (UDP/IP) to port 123. The last eight bytes of the packet included the time of the request, T_1, as obtained from the client clock (which is referenced to the same GPS clock as the server).

The server responded to the timing request by returning a data packet. The entire packet is decoded by the client software, including three 64-bit time stamps. These time stamps utilize 32 bits to represent integer seconds, and an additional 32 bits to represent fractional seconds, providing a resolution of 2^{-32} s (233 ps).

One of the time stamps returned by the server simply echoed back T_1, the time when the client made the request (measured by the client). Two other time stamps contained the time, T_2, when the request was received by the server, and the time, T_3, when the server transmitted its response. When the client received the packet, it again queried its clock board and recorded T_4, the time of the packet's arrival. The time difference, *TD*, between the server and client clocks was obtained using the standard NTP equation for clock offset [1],

$$TD = \frac{((T_2 - T_1) + (T_3 - T_4))}{2}. \quad (1)$$

Using these same four time stamps, the round trip delay between the client and server was calculated [1] as

$$RT_{Delay} = (T_4 - T_1) - (T_3 - T_2), \quad (2)$$

where the time interval required for the server to process the NTP request, $T_3 - T_2$, is subtracted from the round trip delay measured by the client clock. Therefore, variations in server processing time did not impact RT_{delay}. For the server utilized in this experiment, $T_3 - T_2$ was typically about 75 µs, but can periodically be much larger (exceeding 1 ms in some cases).

The results of both the time difference and round trip measurements are updated every 10 s on the client system's display and recorded in a file.

Note that in our configuration, both the server and client were referenced to the same clock, so that *TD* in Eq. (1) should theoretically be 0. Any deviation from 0 was due to NTP time transfer uncertainties. Note also that the "divide by 2" in Eq. (1) assumes that the delay from the server to the client is equal to one half of the round trip delay. If this assumption were true, the delays in the path to and from the server would be equivalent and dividing by two would fully compensate for all delays. In practice, however, the incoming and outgoing delays are not equal, and this delay asymmetry contributes to the uncertainty of NTP time transfer.

III. MEASUREMENT CONFIGURATION

The measurement system was configured to sequentially record readings from the same server (described in II.A) using three different LAN configurations. Three consecutive measurements, one from each LAN, were recorded in the same second at 10 s intervals. This process was repeated for a period of 20 days, from 02/28/2015 to 03/19/2015. The following sections describe the three LAN configurations and Fig. 1 provides a diagram.

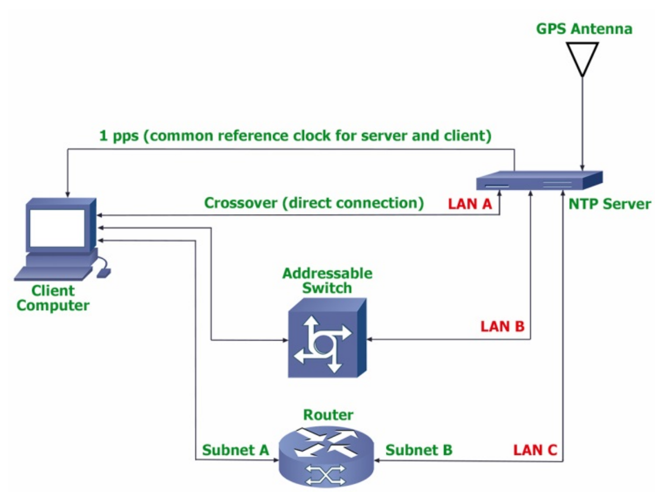

Fig. 1. LAN configurations for NTP measurements.

A. Direct connection to server via crossover cable

A network port of the client computer was connected directly to a port on the NTP server using a Category 6 (Cat 6) crossover cable with a length of 3 m. This represents the simplest possible LAN configuration. The server port had a unique Internet protocol (IP) address to guarantee that the packets were transferred via this connection.

B. "One-hop" local area network

A second network port of the client computer was connected to a LAN port of a 10/100 Mbps router (used here as an addressable network switch). An NTP server port, again with a unique IP address, was connected to another LAN port of the router. The connections in this link were made with two Cat 6 cables, each 4 m in length. This is considered to be a data link layer (layer 2) network path.

C. "Two-hop" local area network

A third network port of the client computer was connected to a LAN on a subnet different than that of the NTP server. The packet sent by the client had to travel through a layer 2 switch and through a router (layer 3) to reach the server subnet. The Cat 5 cables utilized in this LAN configuration were preexisting parts of the NIST network and their lengths are not known.

IV. Measurement Results

The following sections show the measurement results, including the server-client time difference and round trip delay, for each of the three LAN configurations. As noted in Section III, a measurement was recorded from each LAN every 10 s for 20 days (172 800 data points per LAN).

A. LAN A Measurement Results

Figure 2 shows the results of the simplest possible LAN configuration, a direct connection between the server and client via a crossover cable (Section II.A). The average time difference for the entire measurement interval was 0.9 µs with a standard deviation (STDEV) of 9.4 µs. The average RT_{Delay} was 215.1 µs with a STDEV of 17.9 us (approximately 2× the STDEV of the time difference, as expected).

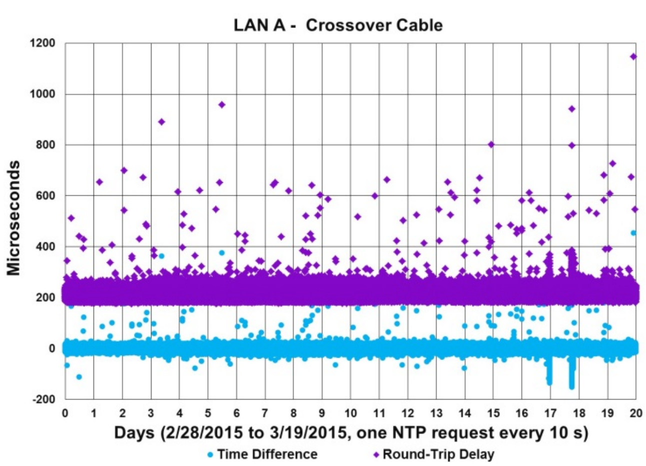

Fig. 2. LAN A measurement results.

Because there is no network asymmetry in this configuration, and very little delay (~0.02 µs round trip) in the crossover cable, nearly all of the round trip delay and all of the uncertainty of the time measurements can be attributed to other factors, as discussed in Section V.

B. LAN B Measurement Results

The LAN B results were slightly worse than LAN A, with the average time difference increasing to 1.6 µs and STDEV increasing to 13.7 µs (Fig. 3). The average RT_{Delay} increased by about 30 µs, to 244.8 µs, with a STDEV of 28.0 us. Again, the STDEV of RT_{Delay} was approximately 2× the STDEV of the time difference, as expected. The slight decrease in performance with respect to LAN A indicates that a small amount of network asymmetry was introduced by the additional hardware, probably because the delay through the addressable network switch is not the same in each direction.

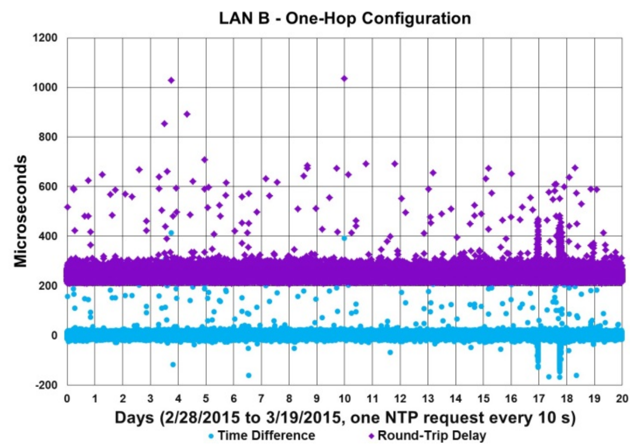

Fig. 3. LAN B measurement results.

C. LAN C Measurement Results

For this "two-hop" LAN configuration, the NTP packets travel to a different network layer and back through a router. This introduces some network asymmetry due to routing, and also due to packet delays, because NTP packets are now required to pass through a subnet that also carried traffic from other computers located in the building (Fig. 4).

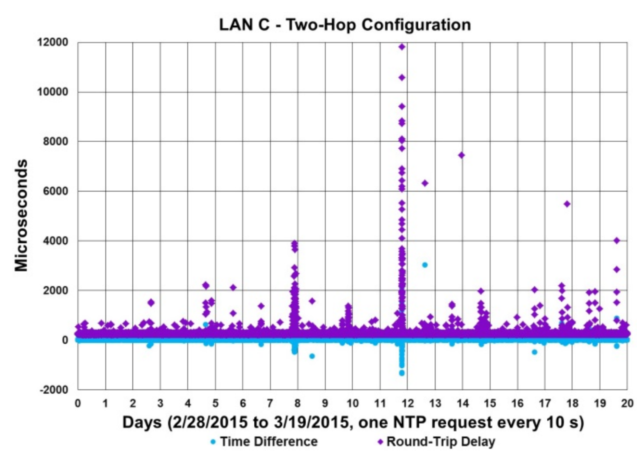

Fig. 4. LAN C measurement results.

The average time difference for LAN C increased to 6.2 µs with a STDEV of 21.5 µs. The average RT_{Delay} increased by less than 5 µs with respect to LAN B, to 249.5 µs. However, the STDEV of RT_{Delay} increased to 96.2 µs, more than 4× the STDEV of the time difference, due to periods when RT_{Delay} increased substantially, briefly exceeding 10 ms (Fig. 2). However, the impact the increase in RT_{Delay} had on the time error was attenuated, suggesting that the packets travelling in both directions were delayed by nearly equal durations as they passed through the router.

Table II summarizes the measurement results. Because the average time difference is smaller than the standard deviation, the shaded columns in Table II represent the combined time transfer uncertainty (1 σ) of a single NTP request. The uncertainty estimates were obtained with STDEV and the time deviation (TDEV), $\sigma_x(\tau)$, where $\tau = 10$ s. The TDEV estimates are slightly smaller but they closely agree with STDEV, which suggests that the time transfer noise is mostly white. For LAN A, the uncertainty is less than 10 µs, for LAN B it is less than 15 µs, and for LAN C it is approximately 20 µs.

TABLE II. SUMMARY OF LAN MEASUREMENT RESULTS

LAN	Statistics (all units are microseconds, µs)				
	Server-Client Time Difference			*Round Trip Delay*	
	Average	STDEV	TDEV, τ = 10 s	Average	STDEV
A	0.9	9.4	8.2	215.1	17.9
B	1.6	13.7	13.1	244.8	28.0
C	6.2	21.5	19.6	249.5	96.2

The time transfer uncertainty can be reduced by averaging over longer intervals. To illustrate this, Fig. 5 compares the TDEV of the results obtained with all three LAN configurations. The uncertainty of LAN C is larger than the other LANs for all averaging intervals, but the time transfer uncertainty (1 σ) for all three LAN configurations is less than 1 µs after approximately 10 hours of averaging.

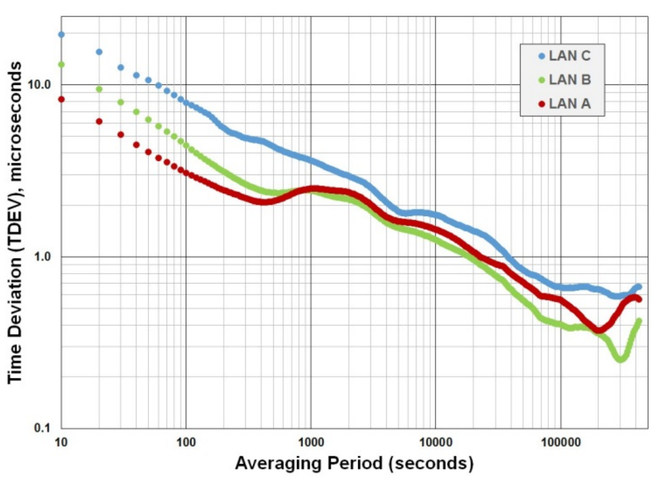

Fig. 5. A comparison of the time deviation of the three LANs.

V. FACTORS THAT LIMIT NTP TIME TRANSFER UNCERTAINTY WHEN NETWORK ASYMMETRY IS ELIMINATED

As previously noted, network asymmetry was eliminated in LAN A, but other factors still limit the uncertainty of NTP time transfer. The three primary limiting factors appear to be client instability, asymmetries in the network interface cards, and server instability, as discussed in the following sections.

A. Client Instability

The uncertainty of the round trip delay measurement in Eq. (2) is dependent upon the client's ability to accurately record T_1 and T_4 by reading the time from its internal clock board. This is analogous to a stopwatch measurement made by a human operator who pushes a button at the beginning and end of the time interval they are measuring. Due to variations in human reaction time, the button will always be pushed early or late by some amount. However, if the start and stop delays are equal, they will not affect the measurement accuracy. In the case of NTP, the clock readings will always have some latency, meaning that the time will always be recorded after it occurs. If the latency of the T_1 reading equals the latency of the T_4 reading, then the measurement of RT_{Delay} will be correct. If the reading of T_4 has less latency than the reading of T_1, then RT_{Delay} will be underestimated. If the reading of T_4 has more latency than the reading of T_1, then RT_{Delay} will be overestimated. The uncertainty contributed to the calculation of TD in Eq. (1) is one half of the error in the RT_{Delay} measurement.

To determine the latency of the client used in this experiment, testing software was written to run in a tight loop on the client computer and to do consecutive clock reads, with no instructions executed in between the clock reads. It was found that on average, the client could read the clock about once every 6 µs. The STDEV was about 0.3 µs, meaning that client instability did not contribute significantly to the uncertainty results summarized in Table II.

Care was taken to configure the client computer parameters to make it more stable than its default "out of the box" condition. The BIOS settings listed in Section II.B were especially effective at reducing noise. Further improvement could be realized by utilizing a real-time OS (rather than a general purpose OS such as Windows 7*) and an SMI-free BIOS.

B. Network Interface Card Asymmetry and Server Instability

To attempt to determine the asymmetry of the client's NIC, the latency testing software was modified to execute a UDP send command in between two successive clock reads. This software sent a standard 48-byte NTP packet through the NIC, but did not wait for a response from an NTP server. The UDP send operation added a delay of 10 µs, increasing the interval between clock readings to about 16 µs. The STDEV doubled, to about 0.6 µs, but was still an insignificant part of the uncertainty values summarized in Table II.

The latency testing software was again modified to wait for an NTP packet to return after the UDP send command was executed. This test is now a measurement of the full round-trip delay, and the server processing time, (T_3 – T_2), was subtracted per Eq. (2). Short tests of this UDP send/receive sequence resulted in a STDEV of ~15 µs, or similar to the result of 18 µs shown in Table II for the entire 20-day period.

If we assume that accounting for server processing time removes the instability of the server (or at least reduces it to a level similar to the sub-microsecond uncertainty of the client), then the large increase in STDEV from 0.6 µs to about 15 µs between the "UDP Send" and "UDP Send/Receive" tests suggests that the dominant source of uncertainty is due to delays introduced by either the NIC of the client or the NIC of the server when a packet is received. For example, delays in the packet received by the client would occur before the client records T_4. Delays introduced in the packet received by the server would occur before the server records T_2.

Our tests were unable to determine whether the client or server NIC was the dominant source of NTP time transfer uncertainty. However, the client NIC is a more likely candidate, as it was designed for general purpose network applications. The server NIC is more likely to be optimized (balanced) for time transfer applications.

VI. SUMMARY

We have measured NTP time transfer performance via three different LAN configurations. The results indicate that the measurement uncertainty (1 σ) of a single NTP timing request when utilized over the simplest possible LAN configuration is less than 10 µs; or at least two orders of magnitude smaller than the uncertainty of a single time request made via the public Internet.

Our measurements have shown that when network asymmetry is eliminated, other (much smaller) sources of uncertainty are revealed, including client instability, asymmetry in network interface cards, and server instability. The delays introduced by the network interface cards when receiving packets appear to be the dominant source of uncertainty. These uncertainties could be further reduced with hardware and software that is better optimized for time transfer, but they can perhaps be considered as the practical limit of NTP time transfer for most applications.

** The measurements were conducted using commercially-available hardware and software products that were made available to the authors. These products are mentioned for technical completeness, but this does not imply endorsement by NIST. Other products may work equally well or better.*

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