Ethernet Time Transfer through a U.S. Commercial Optical Telecommunications Network, Part 2

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BIOGRAPHIES

Marc Weiss worked at NIST from 1979, specializing in time transfer techniques and statistics of timing systems, and is now a contractor for NIST. Marc founded and has led WSTS, the Workshop on Sync in Telecom Systems, annually since 1992. He is the NIST co-chair of the Timing subgroup of the NIST CPS Public Working Group, and has led the NIST program to support GPS since 1980. He has worked on Relativity issues as they relate to GPS and to primary frequency standards. Marc earned his Ph.D. in Mathematical Physics from the University of Colorado, Boulder, in 1981.

Jian Yao is currently a research associate at NIST and the University of Colorado at Boulder, where he performs studies in GPS carrier-phase time transfer and time scale algorithm under the supervision of Dr. Judah Levine. In 2014, he received a Ph.D. degree in physics from the University of Colorado at Boulder.

Lee Cosart is a Senior Technologist with Microsemi. A graduate of Stanford University, his R&D activities have included measurement algorithms and mathematical analysis for which he holds several patents. He serves on, as chair, contributor and editor, the ATIS and ITU-T committees responsible for network synchronization standardization. His TimeMonitor software is used to collect and analyze synchronization and packet timing data and has been used in laboratories and networks throughout the world.

James Hanssen is a research physicist in the Clock Development Division at the U.S. Naval Observatory in Washington, DC. He earned a BA in physics and mathematics from Rice University in 1998 and a PhD in physics from the University of Texas at Austin in 2004. He has been with the Clock Development Division since 2008.

ABSTRACT

There is a need to back up critical timing infrastructure at the national level. This paper provides an update on a joint project employing commercial equipment to send national timing signals through a telecommunication network. This experiment connects the UTC(NIST) time scale located in Boulder, Colorado with the UTC(USNO) Alternate Master Clock time scale located at Schriever AFB in Colorado via a telecommunication provider's optical network. Timing signals using the Precision Time Protocol (PTP) were sent in the usual two-way fashion, but each one-way delay was measured, because we had UTC time scales at both ends of the network that were within 10 ns of each other. This part of the experiment is now nearly complete. The experiment was started in April 2014 and extensions of the project will run through the end of 2016. It appears that there is at least one commercial transport mechanism that could serve to back up GPS for time transfer at the 100 ns level. We found that the asymmetry of the PTP time transfer resulted in 10’s of microseconds of time transfer error, but that the stability through the entire connection was less than 100 ns, as long as the connection remained complete. This implies that if the time delays of the network could be calibrated, it could maintain under 100 ns accuracy as long as it did not go down. We have established the likely causes of the bias, as well as run simulations of various configurations in a laboratory. Thus, we have some certainty that similar results will apply if this technique were used as a service across the country. While many researchers have shown that fiber can transfer time and frequency with high accuracy, this experiment addresses the practicality of using the US telecom infrastructure for timing.

INTRODUCTION

A number of government agencies have discussed a need to back up critical timing infrastructure at the national level [1]. In September 2011, CenturyLink, a Colorado telecom provider, agreed in principle to a two-year experiment linking the UTC time scale of the National Institute of Standards and Technology (NIST) in Boulder, Colorado and the US Naval Observatory (USNO) Alternate Master Clock (AMC) at Schriever AFB in Colorado, where the Global Positioning System (GPS) is controlled. The US Department of Homeland Security (DHS) issued a Request for Information (RFI), Solicitation Number: RUIO-12-A0009 “Transferring of Time via Fiber Network Technologies,” in December 2011, requesting information on how vendors could support this project [2]. One vendor, named Symmetricom at the time, now named Microsemi, provided a detailed plan. A three-way Cooperative Research and Development Agreement (CRADA) was agreed to among NIST, CenturyLink, and Symmetricom-Microsemi and signed in January 2013, to last until January 23, 2015. This has now been extended to January 23, 2017, with the possibility of testing this technique across the US. The original goal of the CRADA was to transfer time through a commercial telecom network with an accuracy better than 1 µs, and a stability better than 100 ns.

The experiment employs the Precision Time Protocol (PTP), IEEE-1588-2008 [3], to transfer time across a public telecom network, with real-time realizations of UTC at each end: UTC(NIST) and UTC(USNO). This has not been done before, to the knowledge of the authors. Microsemi is providing the PTP equipment that transmits and receives timing signals over Gigabit Ethernet (GigE) [4] on optical fibers. The fibers run from the two national timing labs to respective CenturyLink offices, where the signals are multiplexed into their network on a specific optical wavelength that is not shared with any other customers. The experiment has used two different transport methods. The first was to transport the GigE as a Synchronous Optical Networking (SONET) [5] payload on an OC-192 [6] system. The second has been to use the Optical Transport Network (OTN) [7] system to transport the GigE in an ODU0 structure within an ODU2 transport.

PTP employs two-way time transfer, meaning that timing packets are sent in both directions: from the AMC to NIST and from NIST to the AMC. For convenience we refer to the direction from the AMC to NIST as forward, and from NIST to the AMC as reverse.

RESULTS

First we discuss the PTP over SONET results. We found an asymmetry of 40 µs between the forward and reverse directions. The cause is currently unknown. In addition, we found variations in the one-way delay on the order of 300 ns. These were approximately deterministic when nodes were timed by Cs frequency standards, and had more random wander if the nodes were timed by GPS. It may be that the variation during the GPS timing has a sinusoid element. These results are illustrated in the following plots. Figure 1 shows the forward measurements in blue, and the reverse in red. There is a total delay of about 2 ms and the 40 µs asymmetry. A 2 ms total delay at the speed of light would mean a distance of 600 km, or perhaps 400 km in fiber. Given that the distance between the two in a straight line is just under 200 km, it becomes clear that the signals must be buffered and forwarded by equipment in the path. We also note that variations in one direction are somewhat mirrored in the reverse direction. That is, a slope up in one direction is matched by a slope down in the opposite direction. However, the jumps do not seem to be matched.

In Figure 2 we have set the minimum offset of each plot to 0.0 from both paths to see the deviation in the measurements. For most of this period the nodes were timed by Cs clocks, showing a slope of about 50 ns/d with occasional resets of about 300 ns. A period in the middle is marked where GPS timing was used. Here, the system accumulated wander with no clear systematic behavior. There could perhaps be a sinusoid effect.

Following this experiment we switched to using the OTN as the transport. There were two reasons for doing so. First, we wanted to begin to find the cause of the 40 µs asymmetry. Changing the transport was accomplished simply by changing the card that encoded the GigE signals into and out of the CenturyLink network. Switching to OTN would allow us to see if the 40 µs asymmetry was due to the card that encoded the signal into the SONET system. Secondly, we wanted to see if the OTN system would be more stable than SONET. We show plots of the results in what follows. In brief, we found that the OTN data were much more stable, but that the 40 µs asymmetry remained. Figure 3 and Figure 4 show data for the OTN in a fashion analogous to how Figure 1 and Figure 2 show data for the SONET system.

In Figure 3 we see with OTN a similar total delay and asymmetry as for the SONET data, but even here we can see that the data appear more stable. In Figure 4, we set the minimum offset of each plot to 0 as in Figure 2, and we see a peak-to-peak variation of 50 ns over 33 days. Part of this is an apparent trend in the data. In the short term, the stability is 4 ns, which is the resolution of the PTP measurement system we used.

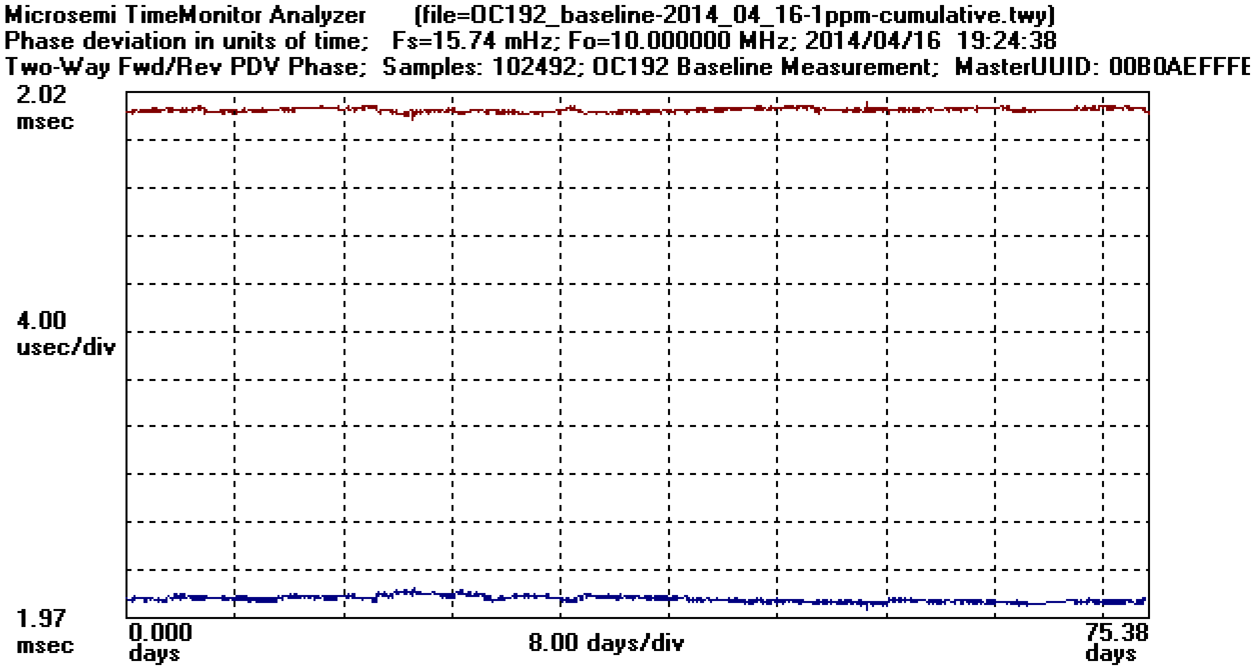

Figure 1: PTP over SONET results over 75 days, showing the forward delay in blue and the reverse in red. The total delay is about 2 ms with about a 40 µs asymmetry.

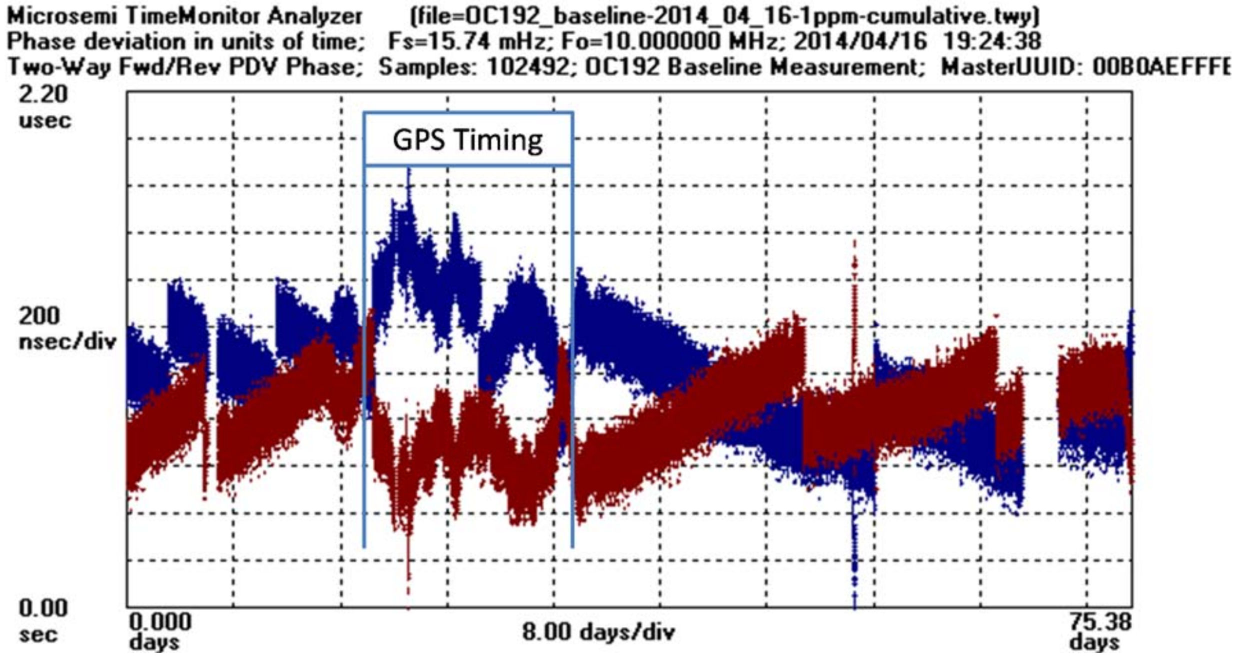

Figure 2: Data as in Figure 1 with the minimum offset of each plot set to 0.0 to show the deviations. For most of this period the nodes were timed by Cs clocks, showing a slope of about 50 ns/d with occasional resets of about 300 ns. A period in the middle is marked where GPS timing was used. Here, the system accumulated wander with no apparent systematic behavior.

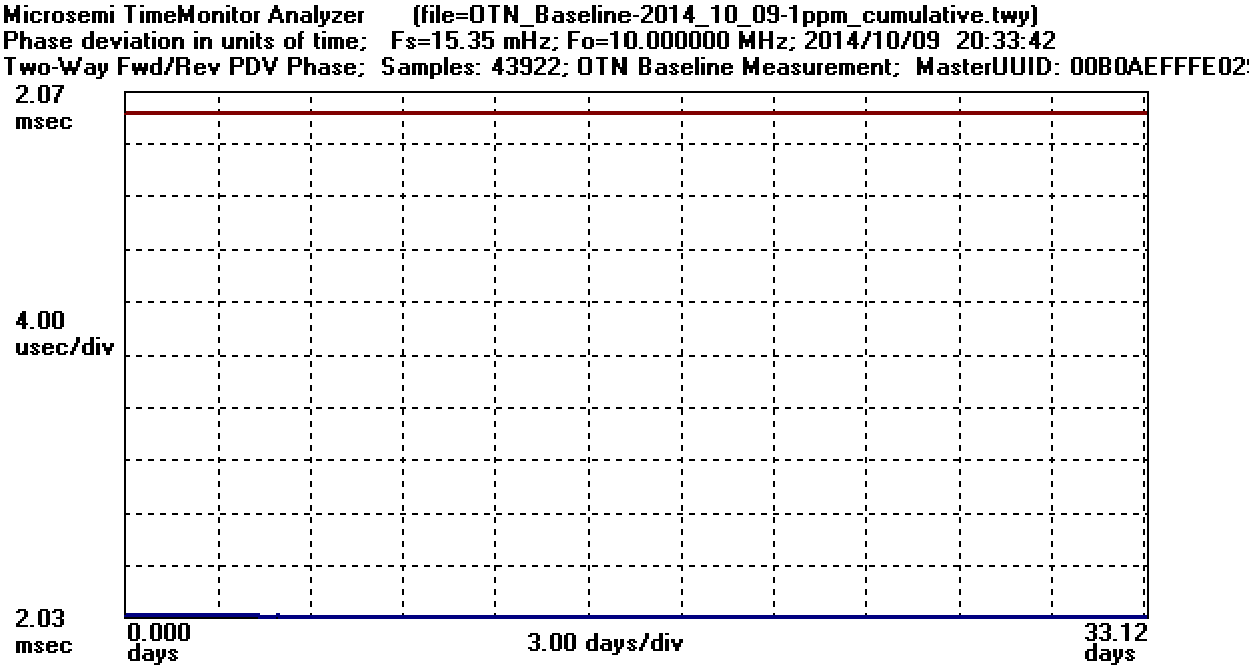

Figure 3: PTP over OTN results over 33 days, showing the forward delay in blue and the reverse in red. As for the SONET case, the total delay is about 2 ms with about a 40 µs asymmetry.

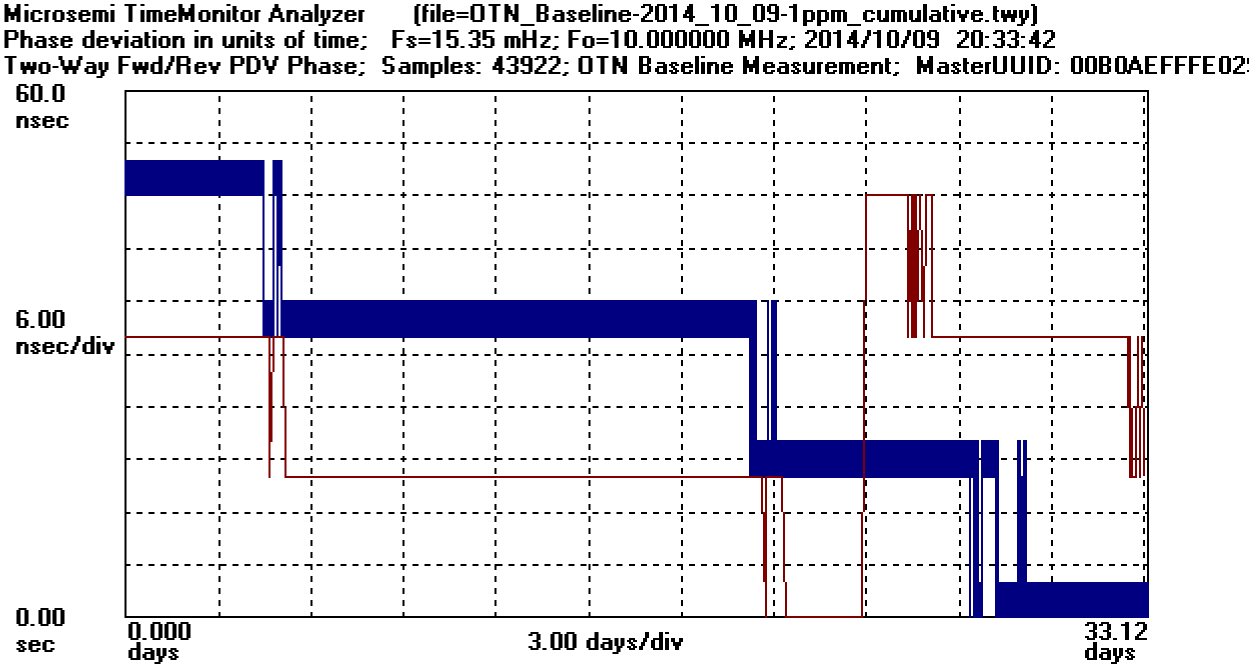

Figure 4: PTP over OTN data with the minimum offset set to 0.0 shows a peak-to-peak variation of 50 ns over 33 days. Part of this is an apparent trend in the data. In the short term, the stability is 4 ns, which is the resolution of the PTP measurement system we used.

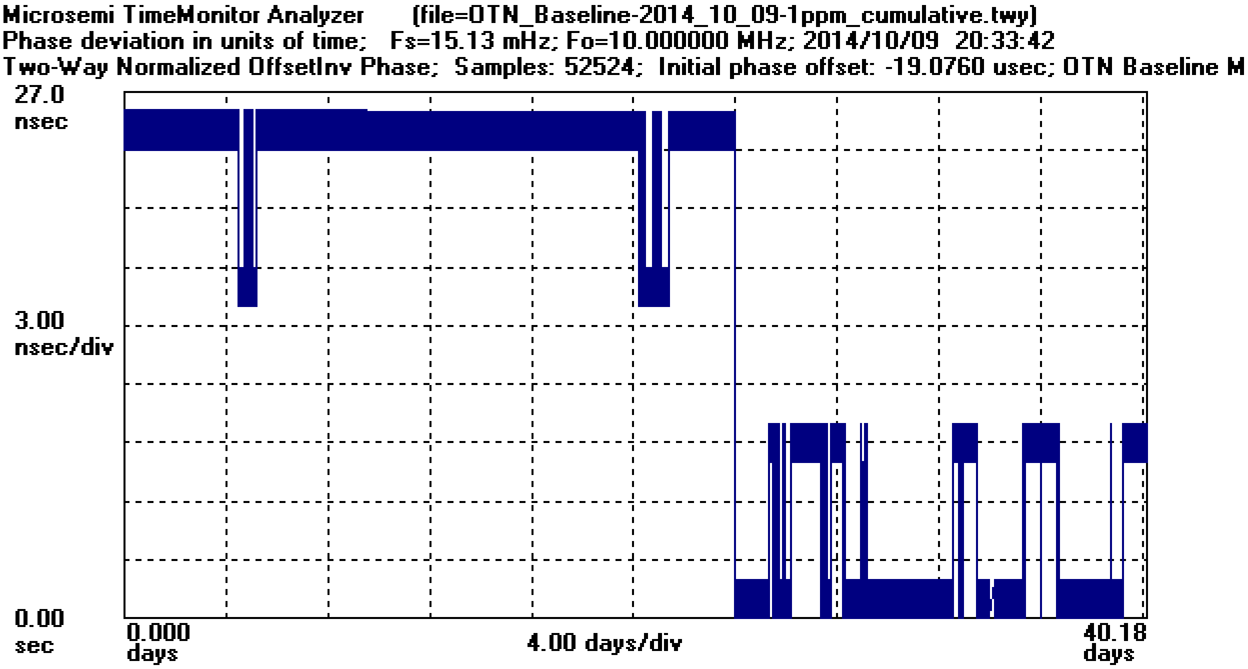

Figure 5: Time transfer capability using the OTN. The initial phase offset of -19.1 µs stated in the header is due to an asymmetry of 38.2 µs. The peak-to-peak deviation is 26 ns, with the short term deviation no more than 4 ns.

Time transfer is achieved in a two-way system by subtracting the data taken in one direction from those taken in the other and dividing by two. This cancels the time transfer errors that are in common in both directions. In Figure 5 shows we subtract the forward packets from the reverse and divide by two, over a 40 day period. We see a peak-to-peak deviation of 26 ns, and a time transfer offset of -19.1 µs. This is the time-transfer capability of this system if used independent of any other time transfer system, such as GPS.

The initial phase offset stated in the header of Figure 5 of -19.1 µs is due to a delay asymmetry between the path delays of the forward and reverse directions of 38.2 µs, since we have divided the round trip path delay by 2. This is about 2 µs different from the 40 µs value shown in previous Figures. We discuss the reason for this in the next section.

DIAGNOSTICS

Initially, we performed a number of loopback tests from NIST to various locations in the circuit between NIST and the AMC. Note that the loopback was actually a loop-back of the two directions individually, i.e. the forward and reverse directions each went from one port of the NIST PTP device out and back to another port of the same device. This method was unable to detect any one-way asymmetry, since it would cancel in the loop back. What we were able to measure here was an asymmetry in the initial hardware that converts the GigE to an ODU0 transport structure and vice versa. The manufacturer was able to confirm that these devices have a random asymmetry of up to 3 µs that cannot be controlled. In the circuit between NIST and the USNO AMC, there is one of these devices serving each end, thus this could account for up to 6 µs, but not 40 µs. When the loop-back circuit that goes through only one conversion device is brought up, measured, then released and re-created and measured again, we do indeed see variations of no more than 3 µs. This could explain why the total asymmetry in Figure 5 is approximately 38 µs, while in Figure 1 and Figure 3 it is about 40 µs.

Next we pursued the cause of the 40 µs asymmetry by breaking the circuit into sections. The path from NIST, Boulder to the AMC at Schriever AFB was chosen to have three segments, by breaking it in a Denver office and in a Colorado Springs office. PTP time transfer was set up from each of these offices to both NIST and the USNO AMC. This required the use of additional equipment, as PTP masters were installed in each of these central offices (CO) using GPS as a UTC reference. Comparing each UTC realization allowed an uncertainty in the references of no more than a few 10’s of nanoseconds, i.e. comparing UTC(NIST), UTC(USNO) at the AMC, and UTC(USNO) as transmitted by GPS.

We found a number of useful results. By combining the asymmetry from NIST to a CO with the asymmetry from the AMC to the same CO, we computed what the asymmetry would have been if this circuit broken at a CO was in fact a connection between NIST and the USNO AMC. We found a large variation in the total asymmetry between NIST and the AMC. Table 1 below shows that the asymmetry varied from 30.2 μs to 46.5 μs, a range of 16.3 μs.

Table 1

	AMC to NIST delay	NIST to AMC delay	Asymmetry
Direct circuit	2025 μs	2066 μs	40.5 μs
Circuit broken in Colorado Springs	2270 μs	2300 μs	30.2 μs
Circuit broken in Denver	2232 μs	2278 μs	46.5 μs

After we measured the PTP one-way delays at each CO to each of NIST and the AMC, we then measured the change in these one-way delays upon a reset of various network elements in the path, and the computed resultant asymmetries between NIST and the AMC. We were able to understand this 16.3 μs variation as caused by restarting various pieces of equipment in the path. We found a number of network elements that caused a different asymmetry when the circuit was re-enabled through the device. If we add up all the changed asymmetry values that we found for each device and for the asymmetries measured to the AMC plus the asymmetries measured to NIST the total changes in the full path asymmetry was 14.5 μs. Because we do not know the cause of these changes in each piece of equipment, nor the potential maximum change, we can assume that these changes in the circuits are consistent with the changes we found in Table 1. We also found that the asymmetry was constant well-below a level of 100 ns as long as the circuit remained operational.

LONG-TERM MEASUREMENTS

A last effort has been made to take long-term measurements and compare them to GPS carrier-phase time transfer. The carrier-phase method used is a method developed by J. Yao that eliminates the boundary discontinuities previously seen [8] [9]. Figure 6 shows a comparison of these two over 28 days. This particular PTP system does not have the precision to show the nanosecond granularity between UTC(NIST) and UTC(USNO). However, the stability of the PTP system over this OTN protocol is under 20 ns for the entire period. By contrast, we can see in Figure 7 that the remote measurement via PTP compares well with the local measurement during a period when there was a failure in a piece of timing equipment. The precision of 4 ns with 16 ns steps in the PTP system can be seen here. This suggests that the underlying OTN communication protocol might support time transfer at the nanosecond level, if the PTP equipment were designed to support sub-nanosecond measurements. Figure 8 shows a longer run of 68 days. The peak-to-peak deviation of the entire run was 26 ns, supporting the possibility that this method would provide time holdover below 100 ns indefinitely, as long as the circuit remained functional. The Modified Allan Deviation of the data in Figure 8 is shown in Figure 9. We see that this system supports frequency transfer approaching 1 part in 10^{15} after 10 days of integration.

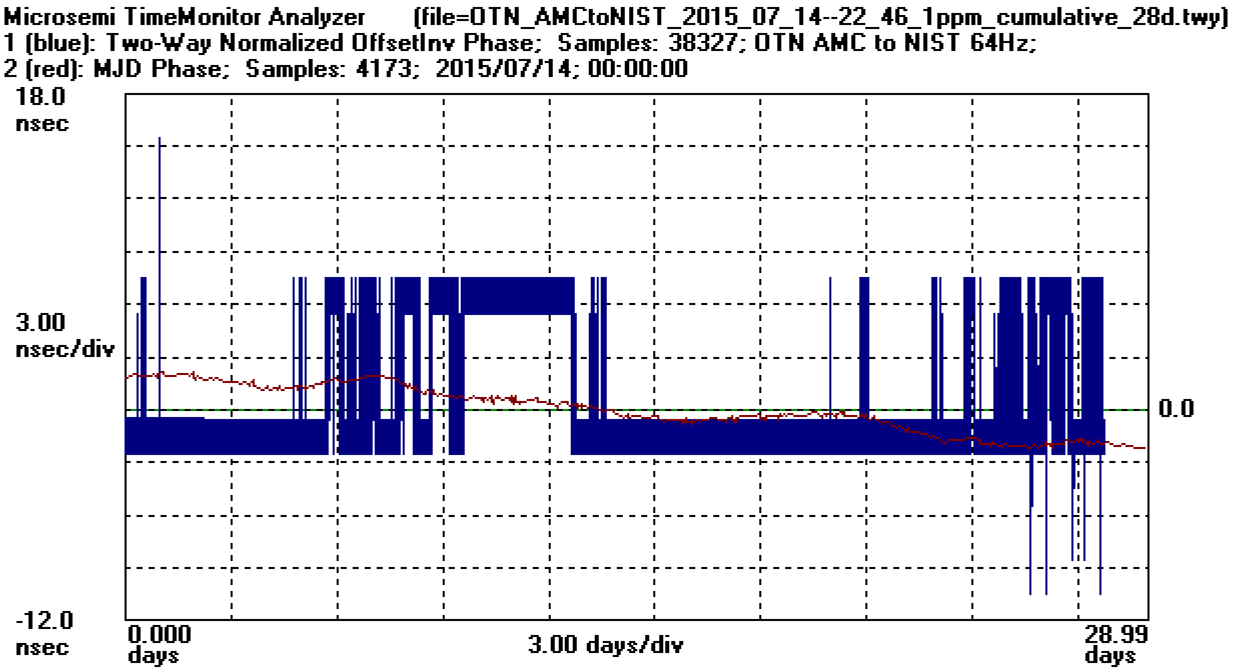

Figure 6. A comparison of PTP fiber time transfer with GPS carrier-phase. The PTP data are in blue, the GPS data are in red. It appears that these particular PTP data do not have the precision to see the small changes between UTC(NIST) and UTC(USNO).

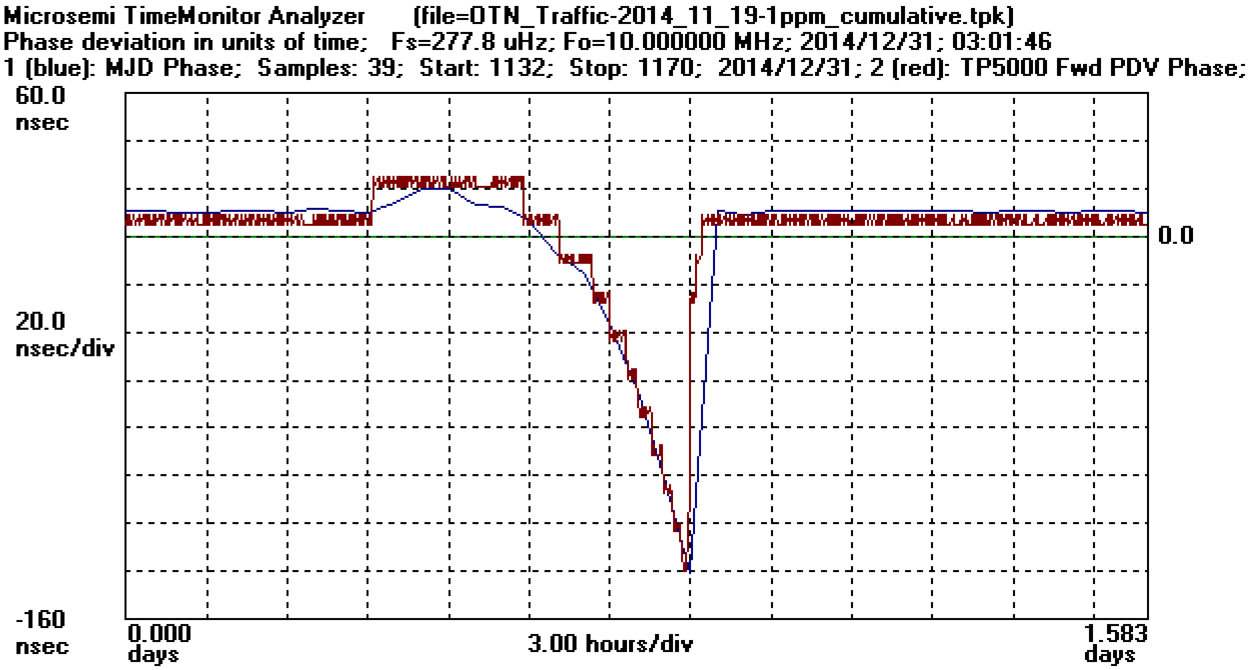

Figure 7. During a period with a failure of timing equipment, the PTP remote measurement (red) matches the local measurement (blue). The 4 ns PTP precision and 16 ns granularity of steps are visible.

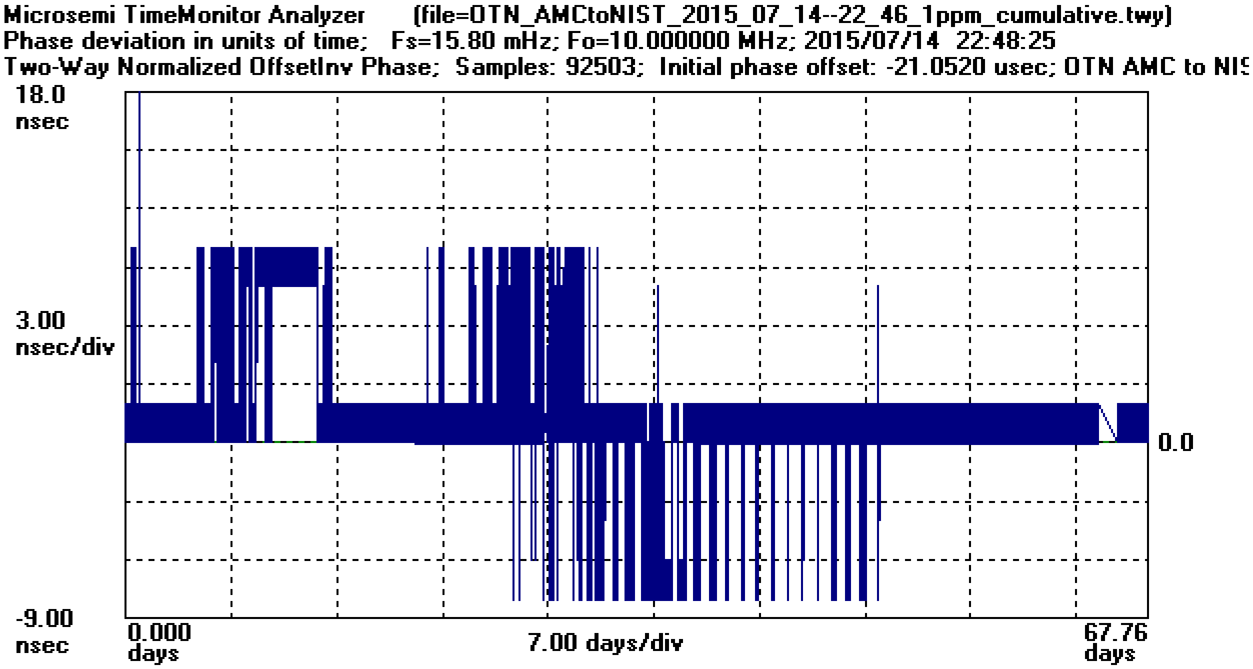

Figure 8. A long-term run of 68 days between NIST and the AMC. The peak variation is 26 ns, showing that this method is capable of maintaining time transfer well below 100 ns.

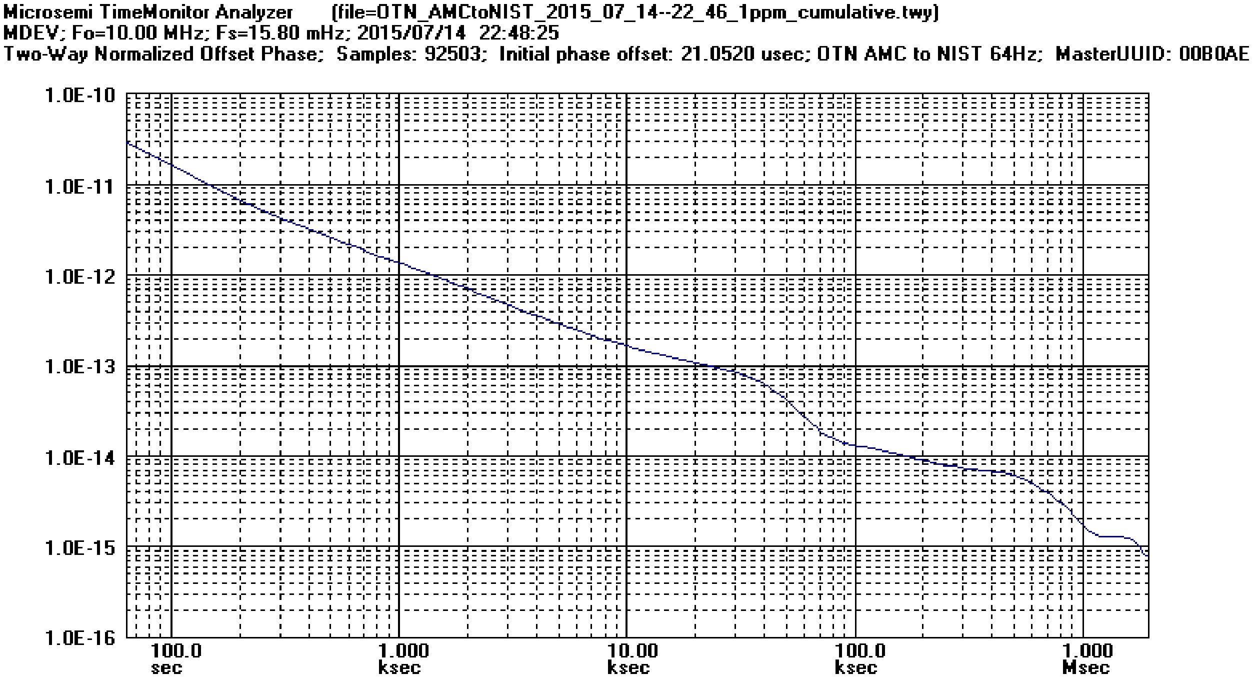

Figure 9. The Modified Allan Deviation of the data in Figure 8. This shows that the capabiltiy of frequency transfer approaches 1 part in 10^{15} at an averaging interval of 10 days.

CONCLUSIONS

While we have not found a time–transfer accuracy below 1 µs, with the OTN system the stability is well below 100 ns. If we can imagine a partial backup to GPS timing, where GPS can be used to calibrate the asymmetry, and where PTP is available for when GPS is unavailable, then it appears that this OTN system would support better than 100 ns time transfer. However, if for any reason the circuit is lost and re-created, GPS or some alternative time reference would be needed to calibrate the new asymmetry. Telecom companies go to great lengths to ensure that their equipment never loses power. Nevertheless, failures do occur. For a truly critical piece of infrastructure that required a GPS timing backup, two completely independent paths could be used, with independent equipment at each end. In this way, the possibility of a timing failure, or even an effect due to timing interference would be highly unlikely to disturb the critical infrastraucture.

It would be useful to extend this experiment to ensure that the values still apply when signals are sent over longer distances, such as across the country.

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DISCLAIMERS

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REFERENCES

[1] Government Accounting Office, "GPS DISRUPTIONS," November 2013. [Online]. Available: http://www.gao.gov/assets/660/658792.pdf.

[2] Department of Homeland Security, "Transferring of Time via Fiber Network Technologies," December 2011. [Online]. Available: https://www.fbo.gov/?s=opportunity&mode=form&id=c73406e809c173ad730f73ab79d5f72a&tab=core&_cview=0.

[3] IEEE, "IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems," 2008. [Online]. Available: http://ieeexplore.ieee.org/xpl/mostRecentIssue.jsp?punumber=4579757.

[4] Wikipedia, "Gigabit Ethernet," September 2014. [Online]. Available: http://en.wikipedia.org/wiki/Gigabit_Ethernet.

[5] Wikipedia, "Synchronous optical networking," September 2014. [Online]. Available: http://en.wikipedia.org/wiki/Synchronous_optical_networking.

[6] Wikipedia, "Optical Carrier transmission rates," October 2014. [Online]. Available: http://en.wikipedia.org/wiki/Optical_Carrier_transmission_rates.

[7] Wikipedia, "Optical Transport Network," September 2014. [Online]. Available: http://en.wikipedia.org/wiki/Optical_Transport_Network.

[8] J. Yao and J. Levine, "An improvement of RINEX-Shift algorithm for continuous GPS carrier-phase time transfer," in *Proc. 27th ION GNSS+ Meeting*, 2014.

[9] J. Yao, I. Skakun, J. Zhiheng and J. Levine, "A detailed comparison of two continuous GPS carrier-phase time transfer techniques," *Metrologia,* vol. 52, no. 5, pp. 666-676, 2015.