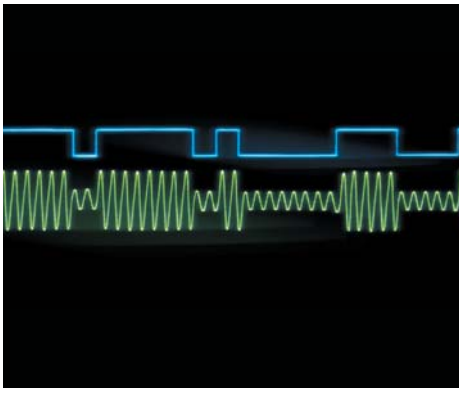
Symmetricom

Designing and Testing IEEE 1588 Timing Networks



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ABSTRACT

IEEE 1588 Precision Time Protocol (PTP) is an emerging technology that facilitates precise time and frequency transfer over Ethernet networks. Synchronization-critical applications can see significant cost and performance improvements over existing alternatives. This white paper compares PTP with other technologies, explains how it works, describes performance criteria, and provides guidance for implementing PTP networks. In particular, this paper presents the results of synchronization tests using hardware time stamping and the IEEE 1588 protocol. It discusses the limitations, advantages, and disadvantages of using PTP for time and frequency distribution; considers PTP performance under various network topologies and traffic scenarios; and shares the test results of PTP performance over networks comprised of commercial off-the-shelf (COTS) network switches and hubs versus PTP-optimized devices.

PTP OVERVIEW

Comparison to Other Technologies

The IEEE 1588 standard [1] defines Precision Time Protocol (PTP), a method to propagate precision time and frequency between networked devices.

PTP offers several advantages:

- Sub-microsecond synchronization.
- Data, synchronization, and management over Ethernet (versus separate dedicated coaxial cables for IRIG).
- Automatic correction for latency.
- Simplified administration: PTP devices autodiscover other PTP devices and form an optimized timing network.

PTP is a recent entrant among a group of mature synchronization technologies. Table 1 compares PTP with IRIG and NTP, two dominant technologies in measurement systems and network synchronization.

Table 1 Comparison of Features by Technology

	IEEE 1588	IRIG	NTP
Peak Error	100 ns - 100 µs	10 µs	1 - 100 ms
Network Type	Ethernet	Dedicated coaxial	Ethernet
Typical Extent	A few subnets	1 mile over coaxial	LAN/WAN
Style	Master/slave	Master/slave	Peer ensemble Client-Server
Protocols	UPD/IP-Multicast	-	UDP/IP-Unicast (mainly)
Latency Correction	Yes	User input cable length per slave	Yes
Network Admin.	Self organizing	Configured	Configured
Hardware at Time Client	Required for highest accuracy	Required	No
Update Interval	~2 Seconds	1 PPS	Varies, minutes

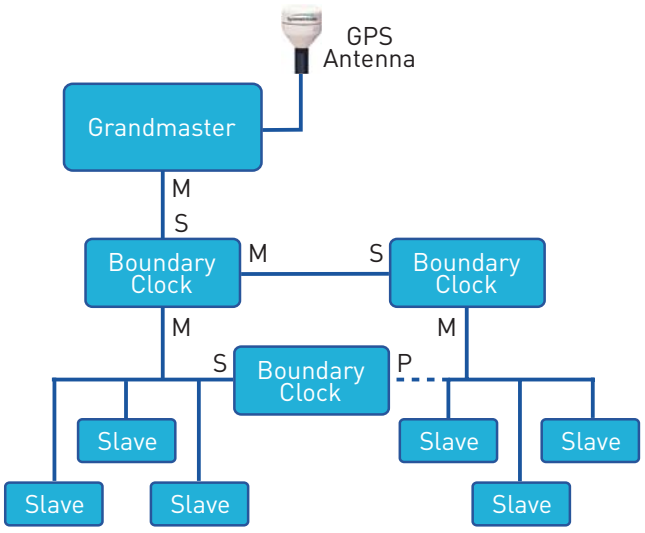
PTP Timing Hierarchy

PTP devices function autonomously, discovering other PTP devices on the network and automatically configuring themselves into an optimized tree-structured timing hierarchy. This results in flexible robust timing networks and eliminates configuration of individual devices, reducing workload during system setup.

Each PTP-capable network port on a device uses the *Best Master Clock* (BMC) algorithm to evaluate the other PTP devices on the network and determine its role as master (M), slave (S), or passive (P), as shown in Figure 1.

At the top of timing hierarchy is the *grandmaster* clock. Grandmasters are frequently equipped with an external timing reference source such as a GPS receiver. High availability systems can be equipped with redundant grandmasters. If one of the grandmasters degrades, the timing hierarchy reorganizes around the remaining one.

Figure 1 PTP Timing Hierarchy

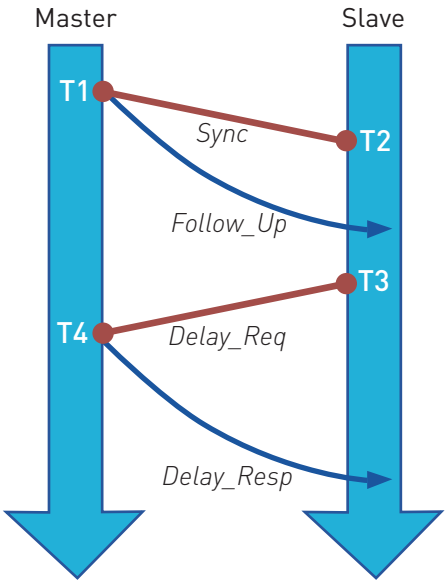


For a thorough discussion of the BMC algorithm, network partitioning, and auto configuration, see reference [3].

PTP Synchronization

PTP master and slave devices exchange ***Sync*** and ***Delay_Req*** messages, time-stamping the arrival and departure times of each one (T1, T2, T3, and T4 in Figure 2).

Figure 2 PTP Synchronization Messages



The ***Follow_Up*** and ***Delay_Resp*** messages convey precise T1 and T4 from the master to the slave.

The slave uses T1, T2, T3, and T4 to calculate its offset and one-way delay relative to the master (Figure 3), and then uses that information to synchronize the slave clock to the master.

Figure 3 Slave Offset and One-way Delay Formulas

One-way delay = [(T2-T1) + (T4-T3)] / 2

Slave offset = (T2 – T1) – One-way delay

The accuracy of these calculations relies on symmetric travel times for the *Sync* and *Delay_Req* messages.

CONDITIONS AFFECTING SYNCHRONIZATION PERFORMANCE

For measurement systems, the system designer will most likely select PTP grandmaster and slave equipment on the basis of precision and performance. The grandmaster clock establishes the overall measurement accuracy to the timescale (UTC). However, system-wide synchronization performance depends on several factors, including, but not limited to:

- Slave oscillator quality and PLL control
- Networking equipment
- Network traffic levels
- Network topology

The system designer generally cannot easily modify the slave oscillator and control. However, PTP settings and network design are within the control of the system designer. Through careful network design, synchronization performance of measurement systems can be maintained.

Slave Oscillator and Control

For slave equipment to remain synchronized to a master, its phase must be measured and maintained, and its frequency offset error must be driven to zero often enough to correct for oscillator drift and other environmental conditions that affect oscillator stability.

PTP equipment with hardware time-stamping has measurement accuracies in the tens of nanoseconds. With nanosecond level measurements, the *stability* of the measurement hardware becomes a significant error term. In this case, employing a high-stability oscillator reduces measurement noise and, depending on the design of the slave, improves its ability to discern and filter out network irregularities.

This presents the system engineer with a tradeoff between slave oscillator stability, PTP synchronization interval, and network design. The more often the slave synchronizes, the less stable the oscillator needs to be. Because of this, the system engineer must also be mindful to design a test network that avoids congestion and transmission errors under peak load. If the network experiences excessive timing packet delays[1] or dropped timing packets due to transmission errors, the decrease in regular synchronization events allows the slave oscillator to accumulate time error and degrades the PTP slave timing precision.

Network Device Types and Traffic Conditions

The traffic management features of COTS network *switches* improve network bandwidth capacity but diminish PTP timing accuracy. Switches queue packets when they are in contention for an egress port by delaying one of the packets and then transmitting the two packets in sequence. This characteristic significantly degrades PTP timing accuracy even with moderate traffic because it introduces variable delays to the travel times of the *Sync* and *Delay_Req* messages.

The potential for timing packets to be impeded by other packets exists, regardless of light or heavy traffic, short or long packets, or whether the packet has priority or not. Slave timestamp filtering can mitigate this problem, however robust algorithms are still under development.

In contrast with switches, COTS network hubs have no traffic management features and rebroadcast all packets with little delay or variability. This provides good PTP timing performance in small networks under low traffic conditions. But in larger networks with more traffic, the broadcast behavior of network hubs causes network collisions that decrease the successful delivery of *Sync* and

[1]PTP slaves may reject excessively delayed timing packets.

Delay_Req messages. With longer, irregular, intervals between *Sync* messages, the slave's timing performance degrades based on its oscillator type and steering algorithm.

The solution is to use switches that support IEEE 1588, known as boundary clocks and transparent switches. These devices are designed to overcome variable latency due to packet queuing in ordinary switches. Based on our measurements, these devices perform better than COTS switches under data traffic load. How *boundary clocks* and *transparent switches* achieve this can be found in [2] and [4].

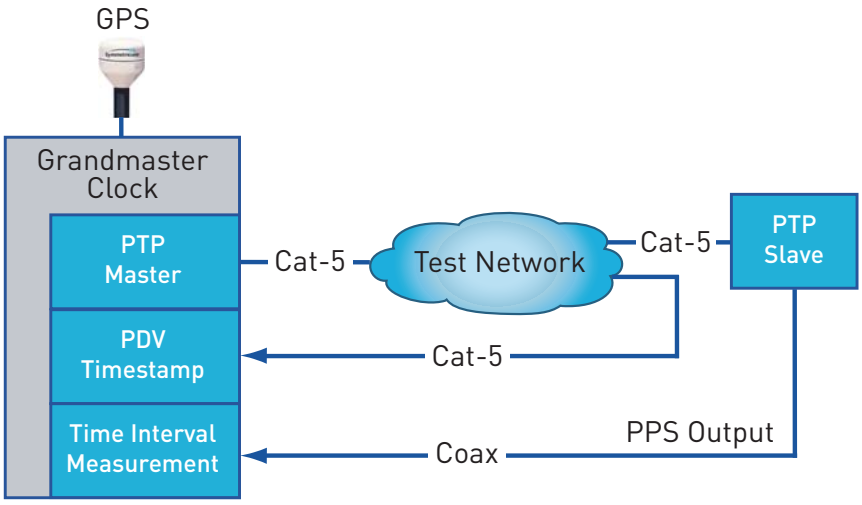
Network Topologies and Characterization

In general, flat network topologies yield better synchronization performance than deep hierarchical networks. Using fewer cascaded network components reduces Packet Delay Variation (PDV). Optimally, timing networks should be kept isolated from data networks until they converge at the slave. To maintain synchronization performance, 1588-optimized switches should be used where data and timing packets pass through a single egress port.

Network characterization is an important step for determining the fitness for high performance synchronization. Two measurements that aid the characterization process are PDV, and Slave PPS Time Error.

PDV measures variations in the master-to-slave packet delay at the physical layer of the network. PDV can be thought of as the input for the slave synchronization servo loop. The larger the PDV and the more random its noise profile, the more sophisticated the servo loop has to be to synchronize precisely with the master. The different classes of network components directly affect the scale and nature of the PDV.

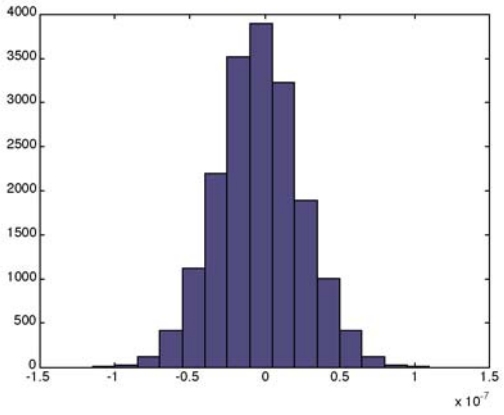
Figure 4 Packet Delay Variation and PPS Time Error Measurement Set-up



Accurate PDV measurements can be obtained using the hardware time-stamping capability of PTP devices. It is essential to measure the reception and transmission of packets at the slave using a reference source that is tightly coupled to the master. This can be accomplished using the same external reference signal as the master (GPS, for example) or by integrating a PDV measurement capability in the master clock, such as the integrated measurement setup shown in Figure 4.

Measuring slave PPS time error from the hardware-generated PPS signals provides direct observation of master-slave end-to-end synchronization. Errors can be viewed using a frequency counter, oscilloscope, or a grandmaster equipped with an integrated time interval measurement input.

Figure 5 Slave PPS Histogram



Plotting a slave PPS as a histogram (Figure 5) shows the statistical nature of the slave synchronization to a master, best described by mean and standard deviation calculations.

Table 2 summarizes slave PPS and packet delay measurements with a variety of network devices.

Table 2 Typical Slave PPS and Packet Delay Through Network Devices

Device	PPS Mean Error	PPS Standard Deviation	Standard Network Delay
Hub	23 ns	22 ns	0.5 µs
Switch1	86 ns	83 ns	15.7 µs
Switch2	-107 ns	111 ns	16.1 µs
Switch3	-16 ns	142 ns	16.3 µs
1588 SW1	24 ns	21 ns	17.6 µs
1588 SW2	-23 ns	27 ns	18.5 µs

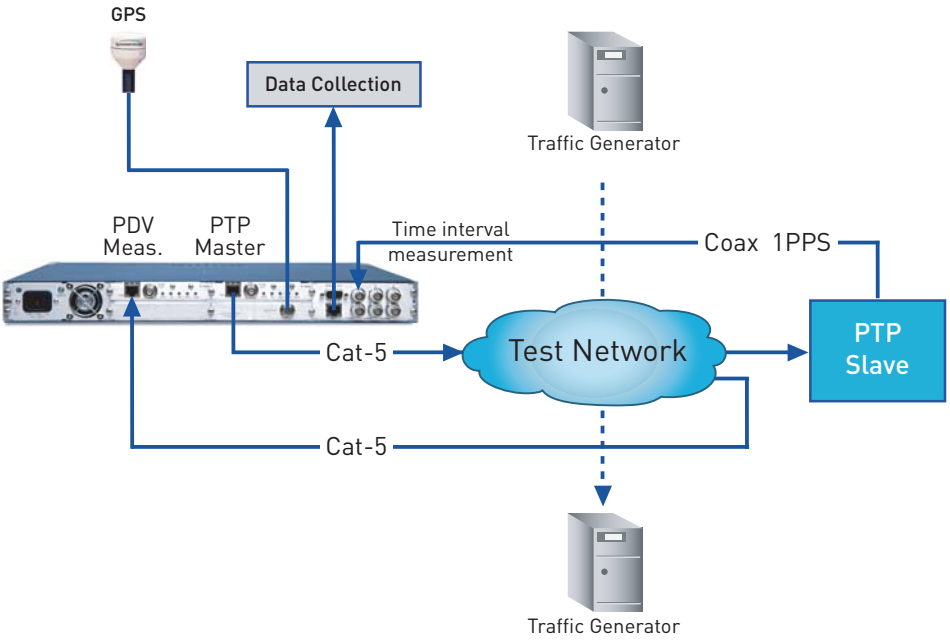
TYPICAL SYNCHRONIZATION PERFORMANCE

Test Set-up

Figure 6 shows a standard set up for measuring PDV and slave synchronization performance through a network cloud.

A measurement controller is used to set up and configure devices and instruments, collect data and modify traffic conditions. The grandmaster clock [5] remains locked to GPS continuously and is customized with additional measurement capabilities. These include a time interval capability for measuring slave PPS outputs and packet timestamping measurement for collecting PDV data on network components. Both of these measurement features take advantage of the precision clock within the grandmaster, delivering high accuracy PPS and PDV data. The slave device [6] is a commercially available development plug-in card with hardware timestamping and PPS signal. TFTP ([7], [8]) file transfers are used to generate data traffic between two workstations. TFTP provides the option to specify the block size of the file transfers. This can be used to vary the length of the packet traffic. The block size of 128 bytes was used for the results reported in this paper, yielding a packet length of 146 bytes. Ethereal [9] is used as an analysis tool to determine traffic levels and general network behavior. The Network components used are widely available small office hubs and switches that support Fast Ethernet (100Base-Tx).

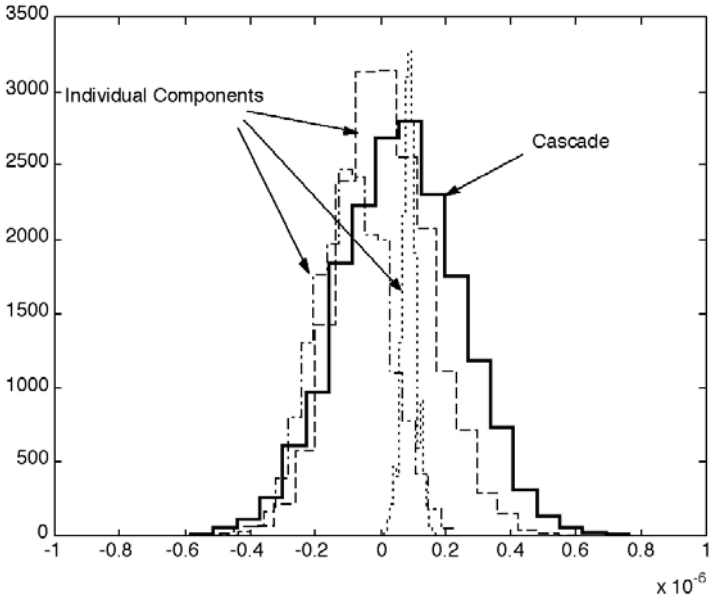
Figure 6
Network Measurement Test Set-up



Results

Figure 7 demonstrates the effect of cascading COTS switches in a PTP timing network.

Figure 7 Cascading COTS Switches



This plot is a set of PPS histograms for the same slave device being synchronized separately through three individual switches and then through the cascade of the three. The cascade PPS performance closely follows the RSS (square-Root-of-the-Sum-of-the-Squares) of the individual switches. Using this principle, the peak slave error of a cascaded network can be approximated by characterizing the individual components. This can be particularly helpful during network planning or when a distributed network makes it difficult to measure the actual cascade across its endpoints. The data also shows how a flat network can gain the benefit of tighter synchronization, like the narrow PPS distribution, while deep hierarchal networks have the broader composite PPS distribution from cascaded switches. Notice the varied performance of different switches.

Figure 8 shows the effects of traffic on a PTP network implemented with COTS switches. The plot clearly shows Packet Delay Variation (PDV) due to timing and data packet contention for the same egress port in the switch. The resulting effects of high PDV upon slave synchronization, shown in Figure 9, are equally significant.

Figure 8 PDV with Traffic

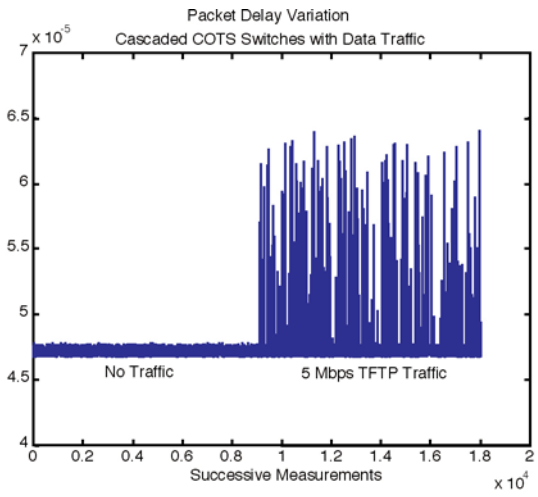
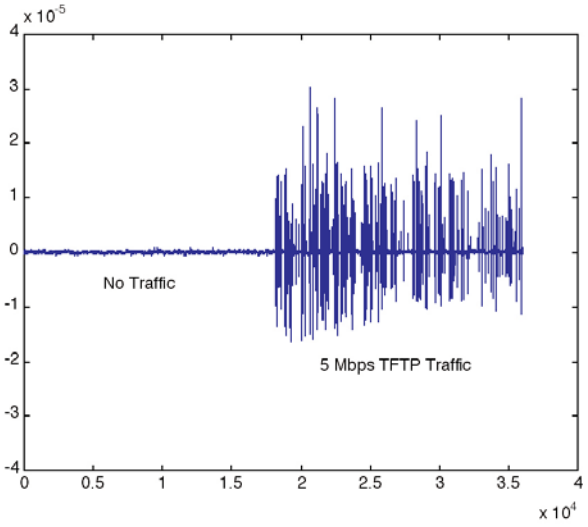
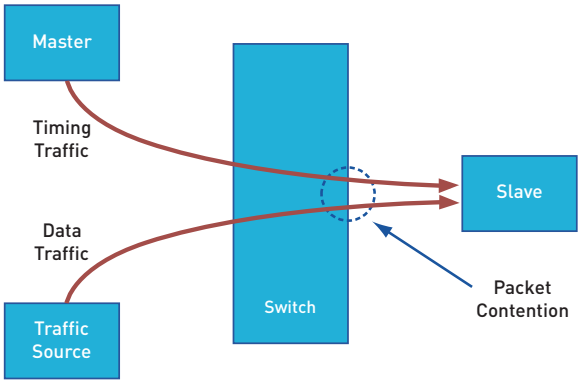


Figure 9 Slave Synchronization Error



To overcome Packet Delay Variation caused by packet contention, a 1588-optimized switch should replace the COTS switch shown in Figure 10.

Figure 10 Simplified Network



The plots in Figure 11 compare the slave PPS time error of a COTS switch with that of a 1588 switch. Both plots show slave synchronization error first without and then with data traffic. The 1588 switch effectively removes Packet Delay Variation due to data traffic.

Figure 11 Sync Error w. COTS vs. 1588 Switch

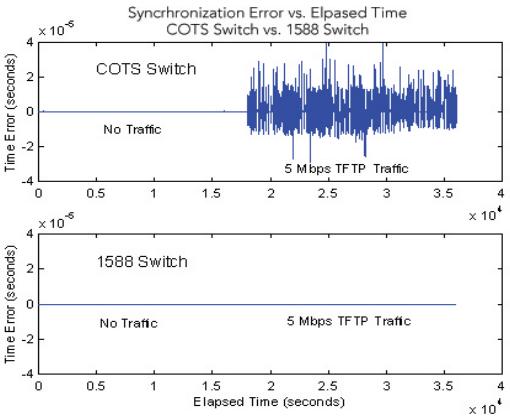
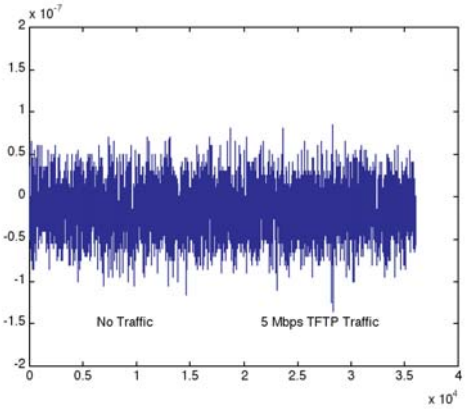


Figure 12 shows PPS error for a network of two cascaded COTS hubs. Synchronization remains unaffected by the 5 Mbps data traffic that starts half way across the plot. Because the two hubs create a single collision domain, the PTP master and slave must wait for a clear communication channel before exchanging messages, ensuring that timing packets traverse the network with low latency. This two-hub network yields good synchronization performance under the light traffic conditions, such as the ones shown here.

Figure 12 Synchronization Error w. COTS Hubs



Under progressively heavier traffic conditions, the PDV on a two-hub network does not change. However, the congestion may delay *Sync* messages, allowing more time for error to accumulate in the slave clock. When that happens, the design and oscillator type of the slave become determining factors in the amount of synchronization time error that accumulates.

CONCLUSIONS

PTP timing networks must be designed correctly and tested to verify that they meet system synchronization requirements under a range of conditions.

The authors recommend that system designers observe the following recommendations:

- For the most accurate synchronization, use 1588 devices that have hardware timestamping.
- Select equipment with a slave design and oscillator type that accommodates the *Sync* interval and the designed network.
- Test network timing performance under targeted real-world conditions.
- Use flat network topologies versus deep cascading topologies for highest performance.
- Avoid COTS switches where high performance is required.
- If using hubs to make network segments, size the segments to meet tight synchronization requirements under peak load.
- Pull data off the timing network as near to the source as possible.
- Use 1588 switches where data and timing traffic packets contend for a single egress port.

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