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Synchronization of the Probes of a Distributed Instrument for Real-Time Ethernet Networks

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Abstract

This work deals with distributed, multi-probe, instrument for performance analysis of Real-Time Ethernet (RTE) network. Particularly, the work is focused on synchronization techniques for distributed measurements. In fact, the accuracy of results (typically jitter and delay) strictly depends on synchronization among distributed probes that sample data.

Three synchronization techniques have been implemented and experimental results are reported. Synchronization by means of an external dedicated 1-PPS signal gives the best results but requires a more complicated instrument structure. On the other hand, a network-oriented synchronization, such as IEEE 1588 PTP or PCTP (PROFINET IO), can simplify time distribution keeping accuracy well below 1 µs.

1. Introduction

Recently, distributed systems have been imposed thanks to computation performance increase and development of communication networks. Both information technology, measurements and industrial applications have taken advantages of this architecture, such as reduction of cabling cost and increase of reliability.

However, distributed applications involve additional requirements and problems, such as ordering of events which happen somewhere in the distributed system or synchronizing actions which take place at remote locations. These requests depend on the time synchronization method among nodes in the system. The difficulty is that the local clock of any device randomly drifts. Several solutions have been proposed in order to overcame this problem: some of them use dedicated hardware, such as GPS ("Global Positioning System") receiver, atomic clock or synchronization signals (e.g 1-PPS – 1 pulse per second), to compensate drift of local clock; others use communication protocols such as NTP ("Network Time Protocol") [1] or IEEE 1588 PTP ("Precision Time Protocol") [2]. Each solution has advantages and disadvantages: only a deep analysis of the application requests (timing performance), and constraints (cost and timing development) can suggest the best choice. For example in some applications the requested synchronization accuracy is below 1 µs, as in automation and control systems or in multi-probe measurement applications for assigning a time reference to logged data (timestamping). Therefore, hardware synchronization solutions are generally preferred.

Commercial network analyzers, such as Endace NinjaCapture 1500 [3] or J6800 Agilent network analyzer family [4], are dedicated to traffic analysis on computer networks, in which information about bandwidth, quality of service and security of the network are the important ones. This is why such instruments normally have single-probe architecture and therefore they don't provide adapted synchronization techniques among devices distributed along the network.

This paper deals with a previously designed multi-probe instrument [5] dedicated to analysis of industrial Real-Time Ethernet (RTE) network (e.g. PROFINET IO, Ethernet/IP, EtherCAT, Powerlink, that are going to be published in the international family standards IEC61158 [6] and IEC61784-2 [7]). The key factor of RTE is determinism and each instrument probe must be able to accurately timestamp RTE frames, in order to evaluate transmission delay and jitter. In this case the accuracy of the measurement instrument strictly depends by synchronization among the probes.

The aim of this paper is to provide the proposed instrument with several synchronization methods and experimentally evaluate them. In fact, there are many scenarios where the proposed instrument can be used, each of them requiring different synchronization strategies among probes. Hence, the possibility to choose the synchronization method increases the instrument usability and assures a wide compatibility. For instance, typical applications are in measurement laboratory (i.e. verification of LXI setup) or industrial environment. (i.e. motion control systems).

In the following section the synchronization of a distributed instrument is introduced. Then, the reference measurement instrument structure is briefly described and three techniques used to synchronize distributed

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probes are presented. Finally, the results obtained from these methods are analyzed and discussed.

2. Accuracy in a synchronization system

Devices of a distributed system obtain local time reference from a clock circuitry. Time reference accuracy results from the quality of frequency source, usually a quartz oscillator. This is an easy and cheap solution but oscillating frequency of a quartz is strongly affected by environmental variations (mainly temperature, but also moisture and mechanical vibrations, a well known problem in literature [8,9,10,11]).

The quality of a clock strictly depends from its frequency stability. Usually noises due to different sources affect the clock frequency. Unfortunately these noises are non-stationary; the traditional statistic instruments are inadequate to quantify the clock stability and special statistic is needed, i.e. Allan deviation (ADEV). The ADEV estimator is written as:

$$\sigma_y(\tau) \equiv \left[\frac{1}{2(N-2)\tau^2} \times \sum_{k=1}^{N-2} \left(x_{k+2} - 2x_{k+1} + x_k \right)^2 \right]^{\frac{1}{2}}$$

where x_k, x_{k+1} and x_{k+2} are time error measurements (i.e. the time difference between the measured clock value and a reference one) made at times t_k, $t_k+\tau$, $t_k+2\tau$ and τ is the sample time between consecutive measurements. The Allan deviation is a measure of how much the average frequency, measured over a time interval τ, changes during the subsequent interval[12,13,14,15,16].

IEEE 1588 defines an estimator derived by ADEV, PTP variance, to describe the stability of a clock and to classify the time sources by means of this information:

$$\sigma_{PTP}^2 \equiv \frac{1}{3} \left[\frac{1}{2(N-2)} \times \sum_{k=1}^{N-2} \left(x_{k+2} - 2x_{k+1} + x_k \right)^2 \right]$$

where x_k, x_{k+1} and x_{k+2} are time error measurements made at times t_k, $t_k+\tau$, $t_k+2\tau$ between the time provided by the measured clock and a reference clock. The sample period τ shall be the sync interval.

When the estimation of frequency drift and offset time among clocks of a distributed system is needed, the traditional statistic is sufficient. It is possible to represent accuracy of a synchronization method using the standard deviation of offset error on measurement interval of N samples:

$$\sigma_x \equiv \left[\frac{1}{(N-1)} \times \sum_{k=1}^{N-1} \left(\bar{x} - x_k \right)^2 \right]^{\frac{1}{2}}$$

where x_k is offset error between the measured clock and the reference clock and $\bar{x}$ is the mean value of the series of offset error during the measurement interval. Moreover, the following parameter is useful to underline the worst case occurred during measurement interval:

$$\mathrm{Max}_x \equiv \max_{1<k<N} \left\{ \left| x_k \right| \right\}$$

Among the methods to implement synchronization in a distributed system, the use of a GPS receiver can guarantee an high level of accuracy (≈100 ns) but it have some problems such placing of the outdoor antenna and its cable (especially in an industrial environment). A clever solution is the use of the same network that connects the device and transports process data to transmit the time information, like NTP does. In details, NTP is a low cost solution used to synchronize PCs on the Internet and it does not guarantee a high accuracy (≈ms). Since measurement and industrial applications require better performance, two other network based methods are presented here: IEEE 1588 PTP (V1) and the proprietary protocols PTCP ("Precision Transparent Clock Protocol").

2.1. Network Synchronization: IEEE 1588

IEEE 1588 is a protocol used for time distribution over a packet network, especially over Ethernet. Compared with other synchronization methods over network (such as NTP), it gives a high accuracy (less than 1 μs) if a suitable hardware assist is provided. It is able to synchronize clocks with different physical features on a local network using limited bandwidth and computational effort.

This protocol select a master clock from other network clock by means of BMC ("Best Master Clock") algorithm. In this way the master time becomes the network reference time. The PTP slave is able to make offset and frequency correction by means of messages exchanged with PTP master (i.e. Sync, Follow_up, Delay_request and Delay_response).

2.2. Network Synchronization: PTCP

PROFINET IO is a RTE protocol for fieldbus application based on Ethernet. There are three different performance classes in PROFINET IO ranging from RT_Class_1 (real time, best effort determinism) to RT_Class_3 (isochronous determinism). The last class is intended for hard real time applications, e.g. motion control, where cycle times below 1 ms with jitter below 1 μs are required. PROFINET IO RT_Class_3 employs the "Precision Transparent Clock Protocol" (PTCP) to synchronize the clocks in all stations and all switches. This allows a precise scheduling of communication also in large distributed systems with many switches. A dedicated hardware support is required in all the RT_Class_3 stations of the network. ASICs are available that provide the requested functionality.

PTCP protocol provides for a hierarchic structure of network clock. The node that transmits frame (PTCP sync) on network for time synchronization is known as PTCP master. The others, that receive or retransmit the messages, are the slaves. The BMA ("Best Master Algorithm") determines behaviour of clocks considering features like clock variance and clock stratum. The sync message is a peer to peer frame. Every node, that receives this message, has to correct its delay by adding bridge delay and line delay in the dedicated field. This mechanism, known also as transparent clock mechanism, is the main difference between PTCP and PTP (V1). Using such a characteristic PTCP is able to compensate the propagation delay (on the network and in the device) of the sync message. Clearly, the PTCP slave is able to correct time offset and frequency drift by means of PTCP sync messages. The rate of this message is set by PTCP master up to one per automation cycle (i.e. up to 1000 per second). In this way, frequency drift can be compensated most frequently.

If analyzed in details, PCTP systems are very similar to PTP systems. But, if the industrial scenario is considered, the diffusion of PCTP will rapidly increase as PROFINET IO RT_Class_3 is deployed in new plants.

3. The multi-probe instrument

Generally speaking, the analysis and monitoring of industrial RTE networks needs high performance instruments, usually implemented by means of dedicated hardware [17] and sometime composed by distributed elements.

The proposed instrument [5] for performance analysis of RTE networks is composed by a network of high performance probes distributed along the monitored network, as shown in Figure 1. Every probe logs the traffic on a RTE network link without altering its performance by means of an Ethernet Tap. The logged traffic and all the information collected by the probes (such as timestamp, frame status, probe status, etc.) are conveyed towards a supervision equipment, called monitor station by means of a high-performance dedicated network: the monitor network.

The monitor station is responsible for storing and analyzing the incoming data transmitted through monitor network without dropping frames. Moreover, the monitor station can set up the parameters of the distributed probes, such as their status (active or less), or their network configurations. It is implemented on a PC; in this way the additional information sent by probes can be extracted with open source programs (e.g. an improved implementation of the well known Wireshark software [5]).

The number of probes that compose a distributed instrument is variable, depending on the specific application. Also the level of traffic logging detail is variable: sometimes it can be useful to record the entire traffic flow, sometimes few details (e.g. packet transit times) are sufficient.

The proposed instrument is scalable and has filtering capability, matching the requirements. However, in order to maintain this flexibility, the architecture has been designed maximising the performance. The monitor network has been realized with Gigabit Ethernet technology, that is faster than traditional (100Mbit/s) RTE under inspection, allowing for full-duplex full-bandwidth analysis.

The probe realization is the key element of the proposed instruments, since synchronization accuracy depends on it (e.g. Physical interface, local time reference adjustment, etc.).

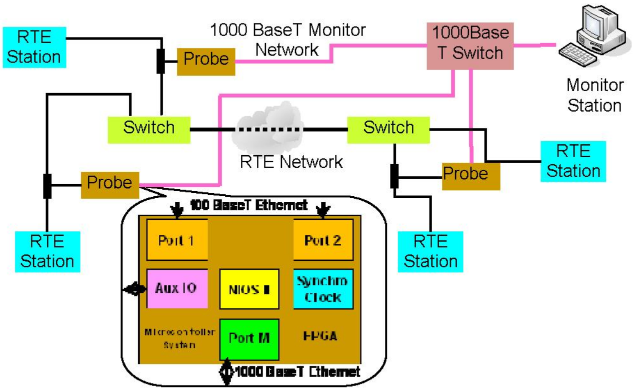

Figure 1. Architecture of the multi-probe instrument.

3.1. Probe architecture

The probe is implemented on a single chip FPGA, as depicted in Figure 1, in order to improve flexibility and to make this solution cheaper and more robust than commercial ones. The probe also supports a microprocessor, the NIOS II by Altera, that is a 32 bit RISC softprocessor. It manages and configures two input ports (Port 1 and Port 2, 10/100BaseT) and a measurement port (Port M, 1000BaseT). The first two ports are used to capture the frames on the target RTE network (10/100 Mbit/s). The other is used to transmit logged traffic and configuration toward the monitor station and to exchange network synchronization frames with other probes. In addition, the hardware provides several auxiliary input/output connections (Aux I/O) used to synchronization and signaling, such as 1-PPS input signal and a RS232 port to manage GPS interfaces. The system reference time is provided by the “Synchro clock” block; it implements all that is needed to synchronize the probe with a reference time using the selected synchronization mode (GPS, external 1-PPS signal or network protocols).

The probe local reference time is provided by an Adder Based Clock in order to compensate both frequency and time drift [18,19]. Two step values can be provided allowing a smoothly offset correction algorithm [20,21].

Probe prototypes have been realized using a NIOS development kit equipped with a EP2S60F672C3 Stratix II FPGA (60k LE). Details on implementation are given in [5].

3.2. IEEE 1588 & PTCP hardware block

An important part of the probe implementation is the "Net Assist" block of Port M. In fact both PTP and PCTP require a low level timestamping unit to operate with the maximum performance. It should be noted that software only implementations of IEEE 1588 exist, but their synchronization accuracy is low, in the order of 1 μs [22]. In Figure 2 is shown the "Net Assist" block diagram.

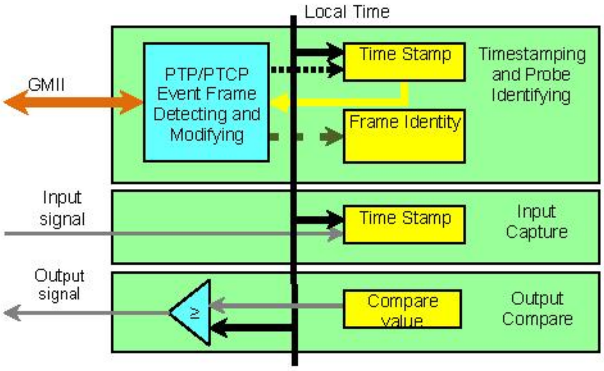

Figure 2. Block diagram of network synchronization hardware "Net Assist".

The developed hardware provides several services to PTP and PCTP protocol stacks. For instance, it timestamps both receiving and transmitting frame on monitoring port by sampling the local reference time at first bit after SFD ("Start of Frame Delimiter") byte as request by PTP protocol [2]. The dedicated hardware can identify transmitted and received Ethernet frames belonging to PTP and PCTP; information about frame type is then provided to the probe controller. In addition, the hardware replaces the timestamp field of transmitted sync or delay request messages (of both protocols) with the precise transmission time value. Thus, the transmission of follow up frames with accurate transmission time is no more needed.

Last, probe gives some extra functionality, useful especially during test and setup: an output signal is generated when local reference time reaches a given value (defined by the NIOS controller); the time reference is sampled on rising edge of an input signal and value can be read by the NIOS controller.

4. Synchronization characterization

The distributed instrument for analysis of industrial RTE has been realized and tested in a two probes version (Figure 3). In the experiments presented in this paper the two probes of the instrument are connected with a HP Procurve1800-8G (J9029A) switch by means of 1000BaseT (Gigabit) connections. The switch is a low cost "ordinary" switch that does not support PTP or PTCP protocols. The timing measures have been made using a high stability counter (Agilent 53132A, option 010). The waveform generator (Agilent 33122A) has been used to generate external timing signal (1-PPS). The high performance network analyzer Endace NinjaCapture 1500 has been used as reference instrument for timestamping and capturing network frames.

Evaluation of instruments performance on RTE analysis and synchronization by means of 1-PPS signal has already been presented in [23]. In following section some of those results are summarized and compared with the results obtained using the implemented network-based synchronization protocols (PTP and PTCP).

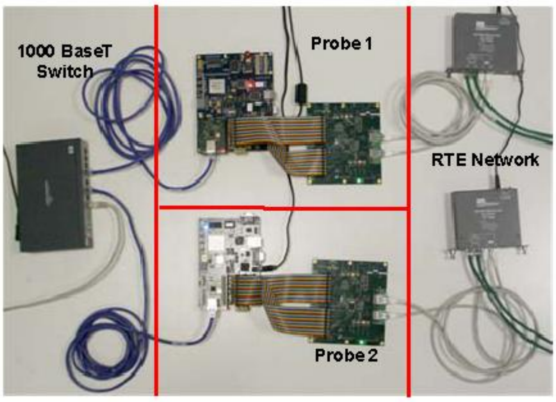

Figure 3. Distributed Instrument for RTE network analysis (2 probes).

4.1. Characterization of the probe local oscillator

The local time reference of the probe is driven by a low cost quartz oscillator. The crystal is a SG8002DC by Epson with a rated stability of 100 ppm. A measurement campaign to calculate the Allan deviation of the local oscillator with respect to the high stability counter (which as been used as reference) has been done. The results obtained over a total measuring interval of 12 hours are illustrated in Figure 4. The oscillator can be classified has a low quality one. This is not a problem, since the synchronization system will take care of its fluctuations.

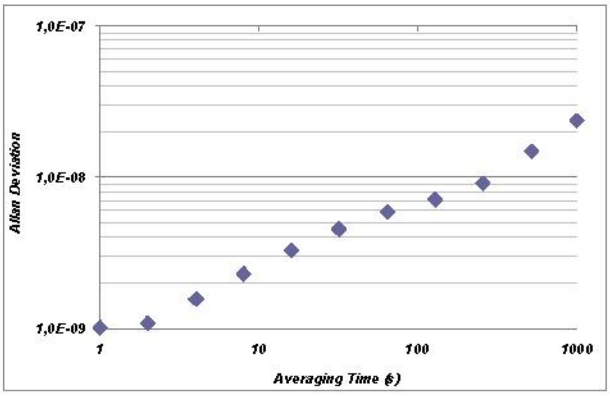

Figure 4. Allan deviation of the local oscillator of a probe.

4.2. Synchronization using 1-PPS reference signal

As a term of comparison, the synchronization method with an external 1-PPS reference signal generated by the waveform generator has been used. In this experiment, the reference signal is provided to all probes using cables of the same length. Every probe offers an output signal related to local reference time.

In Table 1 the offset error between the output signals of the two probes is reported. It represents the time synchronization accuracy. The maximum offset deviation between probes is always less than 84 ns over 4000 measurement samples (2 hours). More measurements about timestamping and capturing capabilities, when synchronization by means of 1-PPS reference signal is used, are reported in [23].

Offset error (ns)		
Ave.	**Std. dev.**	**Max.**
25	15	84

Table 1. Offset error between the two probes using 1-PPS reference signal.

4.3. Synchronization using network based methods

The best performance of a network synchronization method can be reached using a point to point connection. For this reason the first experiment has been carried out linking the probes directly by means of a cross-cable. The Probe 1 is the master of the synchronization system; it transmits the sync message to Probe 2. Hence, the local time of Probe 2 is synchronized with reference time, i.e. time of Probe 1. The offset error between the outputs of probes is a measure of time synchronization accuracy. Table 2 reports the maximum offset between the probes in this case (4000 measurement samples): when sync interval is T_{sync}= 1 s, the maximum offset is 145 ns; if T_{sync} is incremented to 2 s, performance worsen due to the increased drift. There are no differences between PTP or PTCP in the cross-cable case. Figure 5 shows the distribution of the offset error.

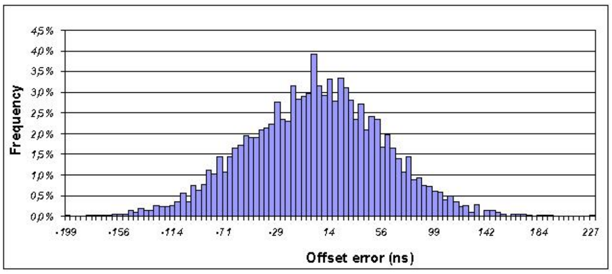

Figure 5. Distribution of the offset error between probes connected by crosscable using the PTP (T_{sync}=2 s).

Next, the experimental setup has been changed as illustrated in Figure 6. The Probe 1 is still the master of the synchronization network but it transmits the sync message through the gigabit switch. As first, the IEEE 1588 protocol has been evaluated. The PTP master (Probe 1) transmits sync messages every 2 second.

Results of experiment are shown in Figure 7 and in Table 2. This connection method is less accurate than the previous, because of unpredictable behaviour of the switch. However the maximum offset between probes is less than 352 ns over 4000 measurement samples.

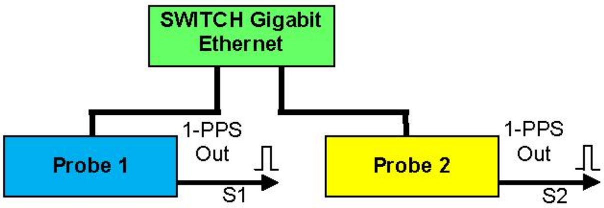

Figure 6. Experimental setup for measuring the synchronization accuracy of network synchronization protocols.

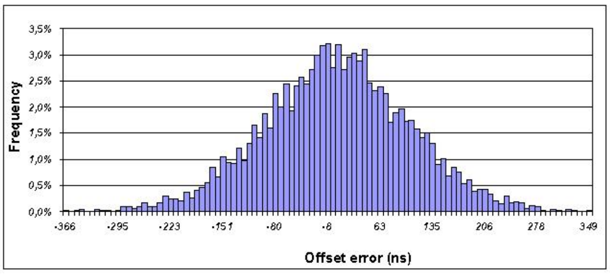

Figure 7. Distribution of the offset error between probes using the PTP (T_{sync}=2 s).

The offset error using an ordinary switch is about the double than the offset error using a cross-cable. However, it is well below 1 µs.

Further, a test has been done while the instrument is working (logging a 100BaseT network). The NinjaCapture has been used to generate full-rate traffic (64byte-long frames @ 100Mbit/s, i.e. the worst case) on a single channel of the RTE links monitored by the two probes. Probes must handle a 100Mbit/s flow of data, which has to be sent to monitor station through the switch. Thus, the switch deals with a data flow greater than 200Mbit/s. Despite the heavy load, the synchronization accuracy is not affected as illustrated in Figure 8 and in Table 2 (4000 measurement sample).

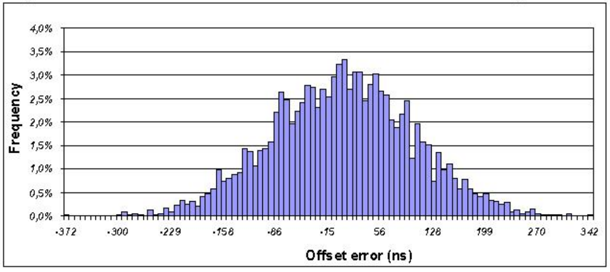

Figure 8. Distribution of the offset error between probes when instruments logs two 100Mbit/s flows (PTP, T_{sync}=2 s).

Generally, the network topology must be carefully designed to improve probes synchronization accuracy and to keep cost low, selecting the right components [24]. The synchronization results could also be improved using PTP compliant switches in the implementation of distributed instrument. Unfortunately, at the time of writing, no PTP compliant Gigabit switch was available in the laboratory.

The experimental setup of Figure 6 has also been used to test the PTCP. Table 2 reports results obtained with a 2 s PTCP sync interval (4000 measurement sample). Figure 9 shows the distribution. As expected this data is of the same order of those presented in Figure 7. In fact the algorithms for synchronization and frequency correction are the same in both cases. The two protocols presented in this paper mainly differ in how they define clock hierarchy and this doesn't affect the synchronization results.

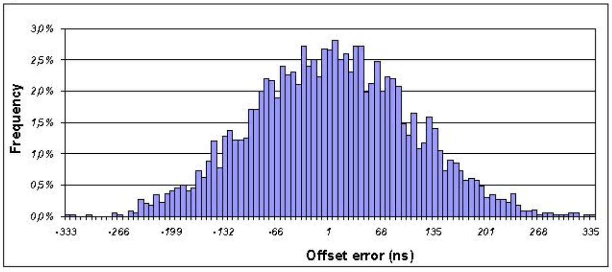

Figure 9. Distribution of the offset error between probes using PTCP (T_{sync}=2 s).

The PTCP can reduce T_{sync} under the limit of 1 s that exists using PTP (version 1). In Figure 10 the results obtained by increasing the PTCP sync messages frequency are reported. Particularly the Probe 1, PTCP master, transmits PTCP sync messages through gigabit switch every 4 ms.

As expected, the standard deviation value is lower than previous one and the maximum offset between probes is always less than 244 ns.

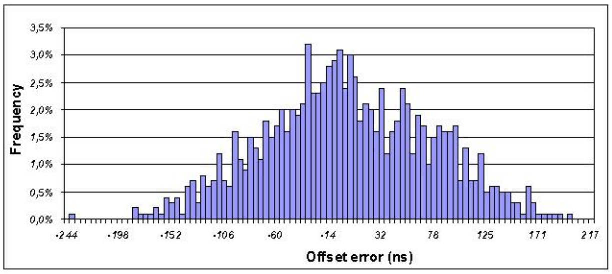

Figure 10. Distribution of the offset error between probes using PTCP (T_{sync}=4 ms).

In fact, a higher sync rate allows a more accurate filtering action, causes a higher bandwidth occupation but yields to negligible performance decrease, as reported in Table 2 (4000 measurement samples).

Protocol	Sync interval (s)	Offset error (ns)		
		Ave.	Std. dev.	Max.
PTP, cross-cable	1	9	40	145
PTP, cross-cable	2	6	54	227
PTP, switch	2	13	95	352
PTP, switch, loaded	2	14	96	358
PTCP, cross-cable	2	10	52	224
PTCP, switch	2	13	100	335
PTCP, switch	0,004	15	73	244

Table 2. Offset error between the two probes in the different experiments.

4.4. Packet capturing and timestamping

The capturing and timestamping capability of the instrument have been tested to verify instrument behaviour. The experimental setup for tests is shown in Figure 11. The network analyzer NinjaCapture 1500 has been synchronized with Probe 1 by means of an external reference signal (1-PPS) generated by the waveform generator. The Probe 1 works also as PTP master, sending PTP sync messages every 2 s to Probe 2 through the switch. The NinjaCapture analyzer has been used as reference instrument. It generates a sample network traffic that is captured by the distributed Probes (Probe 1 and Probe 2) by means of Ethernet Taps. The same traffic flow is captured back by NinjaCapture with the second network interface. The results reported in Table 3 are obtained considering 100000 frames on a time interval of 1000 seconds. The test has been repeated changing direction and frame length (64 to 1522 bytes).

The accuracy in timestamping assignment has been evaluated from offset between timestamp assigned to the same frame by the distributed probes. In Table 3 the offset between Probe 1 and NinjaCapture is also reported. For sake of completeness, the timestamping accuracy obtained in [23], using 1-PPS synchronization between Probe 1 and Probe 2, is also included in Table 3. Figure 11 shows a sample distribution of timestamp offset. The results are consistent with synchronization accuracy reported in Table 2.

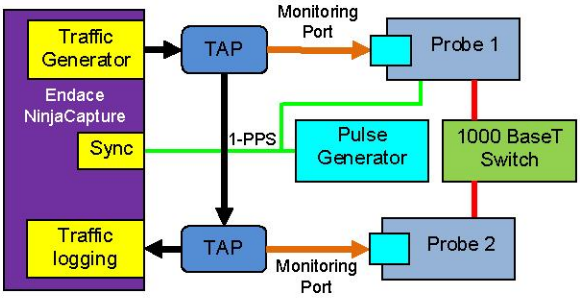

Figure 11. Test setup for measuring timestamp assignment accuracy.

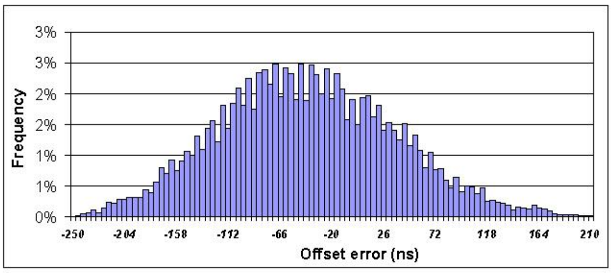

Figure 12. Distribution of timestamp offset between probes capturing the same Ethernet frame (256 byte-long).

4.5. Characterization of the ordinary switch

A rough characterization of the Gigabit Ethernet switch has been done using the experimental setup illustrated in Figure 13. Probe 1 and Probe 2 are synchronized using the 1-PPS signal, therefore they operate with the maximum accuracy. Port M of Probe 1 inject a PTP sync message into the switch every second; such a message contains the true transmission time as discussed earlier. The frame pass through the switch and reach Probe 2 where is received and timestamped. The difference between transmission and receiving time (propagation time through the switch) is computed by Probe 2 and then it is sent to the monitor station.

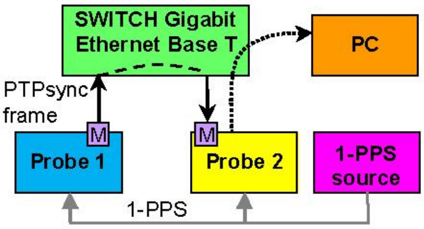

Figure 13. Experimental setup for switch characterization.

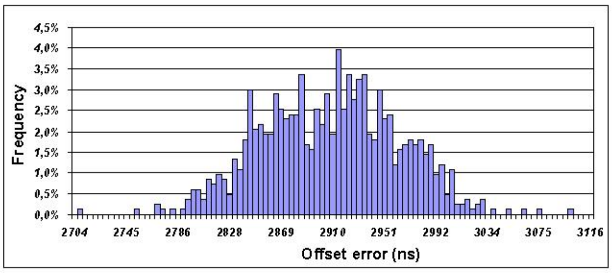

Figure 14. Distribution of the propagation delay of the switch in case of traffic composed of PTP sync frames only.

The result is shown in Figure 14. The ordinary switch has an average propagation time that depends on frame length; in the present case (PTP sync message frame) it is 2900 ns with standard deviation of 55 ns.

5. Conclusion

A new instrument for performance analysis of RTE systems has been proposed. There are several fields of use for such a instrument, but primarily it has been designed for industrial and measurement applications. A key factor for a distributed instrument is an efficient synchronization method to share the time between probes that are located in different places along the RTE network under test.

If an external reference signal (1-PPS) is used, the best accuracy results (σ=15 ns) can be obtained, but this technique has some disadvantages; for instance a dedicated extra wiring is needed.

In this paper, two additional synchronization techniques (i.e. PTP and PTCP) have been implemented and evaluated. They are attractive because use the same network for collect measuring data and exchange synchronization information. The synchronization accuracy is lower than 1-PPS, but it could be sufficient for the largest part of normal application. PTP and PTCP

Traffic flow	Frame length (bytes)	Timestamp offset (ns) NinjaCapt. – Probe 1			Timestamp offset (ns) Probe 2 – Probe 1 (PTP)			Timestamp offset (ns) Probe 2 – Probe 1 (1-PPS)		
		Ave.	Std. dev.	Max	Ave.	Std. dev.	Max	Ave.	Std. dev.	Max
Port 1 to Port 2	64	16	23	93	44	84	347	33	12	107
	256	18	23	106	42	87	315	15	16	114
	1024	18	22	93	46	73	283	21	14	112
	1522	14	26	116	46	87	286	26	19	122
Port 2 to Port 1	64	15	23	123	43	86	308	21	12	111
	256	18	21	99	45	78	254	22	15	119
	1024	19	23	103	42	82	315	22	15	111
	1522	20	25	100	45	80	244	21	18	124

Table 3. Timestamp offset between probes capturing the same Ethernet frame.

are quite equivalent with a standard deviation σ in the order of 100 ns, if a sync interval of 2 s is used. The synchronization accuracy slightly improves (σ=73 ns) using the higher sync rate allowed with PTCP (i.e. 4 ms).

In conclusion, the proposed instrument can be profitably utilized in many situations thanks to the multiple synchronization support and its low cost.

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