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An experimental approach to estimate real-time characteristic of PROFINET IO versus PROFIBUS DP V2

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Abstract: - This paper investigates performances of PROFINET IO Class 1, based on Ethernet@100Mbit/s, as a replacement of PROFIBUS DP V2, based on RS485 @ 12Mbit/s, for the realization of time-critical and isochronous systems.
In this work, two test systems have been built. In the first one, the same experimental setup with the same application has been implemented using PROFINET and PROFIBUS networks and a smart method has been applied to measure time-related characteristic at the application level. In the second one, two PROFINET networks realized with different vendors devices have been compared.
Results show that, with currently available components, PROFINET IO Class 1 RT average performance is close to PROFIBUS DP V2 average performance, whereas PROFIBUS DP V2 applications are more deterministic with a jitter well below PROFINET IO Class 1 applications. Moreover, spread between real-time performances of PROFINET IO devices from different manufacturer is still wide, indicating a rapidly evolving situation.

Key-Words: - Real-time, Industrial Ethernet, Isochrony, PROFINET, PROFIBUS

1 Introduction

Some industrial applications, as packaging, manufacturing, wood machining or plastic extrusion, require high performance systems to achieve cost reduction. Data exchange must be fast, reliable and deterministic. As regard digital communications, latency times must be in the order of hundreds of microseconds to correctly close control loops between twin drives, while jitter times must be lower of one order of magnitude.

There are fieldbuses that guarantee synchronization among nodes of the same network: sampling and actuating is synchronized, allowing control algorithms to reach best performances [1]. Moreover, when network behavior is required to be cyclical and strictly time related (e.g. motion control application) isochronous fieldbus can be used. PROFIBUS DP V2, FTT-CAN [2], FlexRay [3] are examples of isochronous fieldbuses.

However when complexity of the automation task increases, fieldbus technology could rapidly reach its limit, in terms of performances and diagnostic capability. Faster and more flexible solutions are often required by the market that is considering the use of Ethernet.

Ethernet is the natural physical layer of more used protocols (first of all TCP/IP), including several high level protocols for industrial automation (e.g. OPC (Ole for Process Control) technology [4]). The idea to use Ethernet even at the field level took place in the last years thanks to the more efficient switch-based architecture, to the increased transmission rate and to the availability of low-cost devices [5]. Anyway IP based protocols do not guarantee performances suitable for most of real-time control applications, therefore other solutions are emerging, called Real Time Ethernet (RTE), as Powerlink [6], PROFINET IO [7], EtherCAT [8], Ethernet/IP [9], MODBUS-RTPS [10] and so on. These technologies allow more powerful performances if compared to traditional fieldbuses and they will be included in the IEC61784-2 to be released in 2007. First commercial products are available and many others have been announced; they solve the non-determinism problem of Ethernet modifying media access rules by means of software protocols (e.g. master-slave protocols) or thanks to ad hoc switches or network interfaces.

Ordinary instrumentation for Ethernet analysis (protocol analyzers, simulators) can hardly estimate real-time characteristics of RTE networks, so new approaches are needed. The objective of the paper is to experimentally evaluate PROFINET IO real-time behaviour comparing it with other real-time

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fieldbuses.

Today, PROFINET and PROFIBUS are two of the most used fieldbuses in Europe and many vendors offer the same products with both the communication interfaces as options. Consequently, the same experiment can be performed with identical hardware (I/O, PLC) and different communication networks.

In the following, an introduction to PROFIBUS DP V2 and PROFINET IO will be provided; experimental setup will be discussed and, last, experimental results will be presented.

2 PROFIBUS DP V2

PROFIBUS was introduced by SIEMENS in 1989 and today is the fieldbus with the highest number of installed nodes in the world. PROFIBUS DP is defined in the IEC 61784-1 [11] as the Communication Profile 3/1 (CP 3/1) of the Communication Profile Family 3 (CPF 3), relevant to the IEC61158 [12] Type 3 network. PROFIBUS DP can use the RS485 as physical layer (PHY) with a speed up to 12 Mbit/s.

PROFIBUS DP is a master/slave protocol with token passing in order to support a multi-master architecture. A detailed explanation of DP behavior could be found in [13].

Usually, PROFIBUS DP products are classified in base of the old name of the protocol versions: V0 has cyclic data exchange and configuration facilities; V1 supports acyclic data exchange and enhanced engineering; V2 can be isochronous, with timestamps and slave-to-slave communication. DP V1 acyclic data can influence cycle duration introducing jitter [14, 15].

On the other hand, PROFIBUS DP V2 uses the end of a broadcast telegram (GC, “Global Control” type) to mark the beginning of a cycle, as shown in Fig. 1. Due to the nature of the serial link (RS485), every node on the network receives this signal shifted by the propagation delay along the line. This delay is low and constant, so the start of the cycle can be considered synchronized or misalignments can be compensated.

In a DP V2 cycle, DP cyclic data exchange (DEX) is executed just after the GC, followed by acyclic messages and by support services, like new station discovery task (GAP) and token passing slot (TOK). The end of a cycle is left free to facilitate the exact transmission of the next GC telegram. Within PROFIBUS DP V2 the start of a DP cycle can also be employed to lock slave PLL (Phase-Locked Loop) and to synchronize the application level both in the master and in the slaves.

PLL synchronization avoids clock shifting among slaves; all the slaves have the same clock despite they are distributed over a wide area and their oscillators have different crystals.

Application synchronization allows a typical automation cycle to be optimized as reported in Fig. 2. Master application cycle is delayed of time Tm after the completion of data exchange phase, so the master can analyze in cycle #n data sampled in the previous cycle #(n-1). If the master elaboration ends before the start of a new bus cycle, results can be sent to the slave for actuating just in the bus cycle #(n+1). Since slaves operate with an internal cycle faster than the bus cycle, actions related to an input change appear on the output after two bus cycles only. It should be said, for sake of completeness, that PROFIBUS DP V1 supports only synchronization at I/O level (that is sampling and actuating of distributed inputs or outputs can be performed simultaneously on the whole network) whereas applications are unsynchronized.

Today, the diffusion of PROFIBUS DP V2 products is limited to high-end devices, whereas the majority of PROFIBUS products support only version 0 and 1.

Typically PROFIBUS DP V2 is used in Motion Control applications or packaging systems. However, distributed I/O compatible with DP V2 is also available.

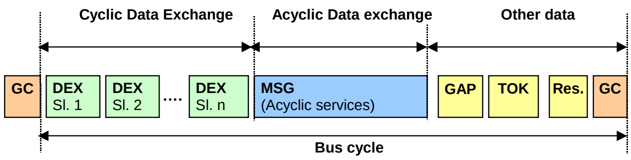

Fig. 1. A bus cycle in PROFIBUS DP V2. The end of the Global Control (GC) telegram marks the begin of a bus cycle.

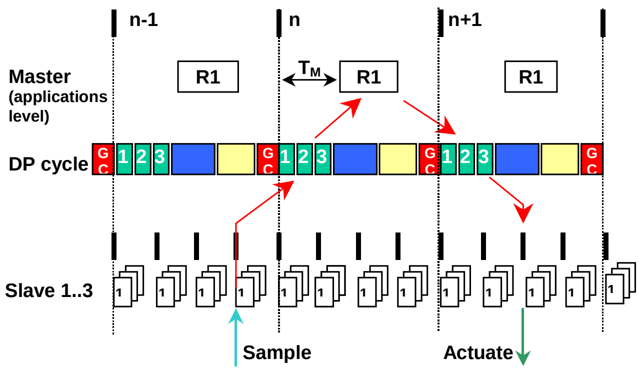

Fig. 2. Optimized application cycle in PROFIBUS DP V2. Only 2 DP bus cycles are required between sampling and actuation.

3 PROFINET IO

PROFINET family comprises two different protocols designed to be employed at different levels of factory communication systems: PROFINET CBA for the high levels and PROFINET IO [16] for the device level. PROFINET CBA is already included in the IEC61784-1 as the CP 3/3 (CP 3/3 PROFINET) of the CPF 3, relevant to the IEC61158 Type 10 network. PROFINET IO will be a part of the new standards on RTE (named IEC61784-2) with three CPs (CP 3/4, CP 3/5 and CP 3/6).

PROFINET IO defines three Classes to classify the Real Time communication performance. PROFINET IO Class 1 and Class 2 (UDP support) are similar; they are suitable for systems requiring cycle time of tenth of milliseconds. Class 1 and Class 2 are often called PROFINET IO Real Time (RT).

PROFINET IO Class 3 includes lower classes and allows use of Isochronous Real Time (IRT) communication for applications with cycle time down to few hundreds of microseconds (far better than PROFIBUS DP V2). In details, PROFINET IO Class 3 is based on a highly precise and synchronized cycle obtained by means of dedicated switches that are capable of estimating the delays they introduce and correcting them. Such switches are ASICs (Application Specific Integrated Circuits) and their introduction in the marker is just begun; this means that no IRT compliant devices are available at the time of writing. For such a reason, this paper deals only with PROFINET IO RT communication implemented by today's existing industrial devices.

Class 1 communication for PROFINET IO takes place directly on the MAC layer of Ethernet: the Ethernet Type that has been reserved is 0x8892. The link speed could be 100 Mbit/s or 1 Gbit/s. The usage of priorities at Ethernet level, defined in the VLAN standard [17], is allowed to speed up delivery of RT frames.

Generally PROFINET IO components are classified into three categories: IO-Controllers, the intelligent deviceswhich carry out automation tasks; IO-Devices, the devices that act as interface between the automation systems and the field (sensors, actuators, IO module etc.); IO-Supervisors, for configuration and diagnostic purposes.

Critical timing requirements of the system are related to the data exchange between IO-Controllers and IO-Devices, because it is executed during the automation task. In opposition, configuration and diagnostic traffic generated by IO-Supervisors is sporadic or concentrated during off line phases, thus it does not need real-time performance.

Run-Time operations in PROFINET IO Class 1 are cyclical as illustrated in Fig. 3, with a scheduling sequence that is continuously repeated by each station of the network.

A cycle begins with transmission of cyclic RT data between stations, followed by acyclic RT data as, for instance, alarms. Finally, portion of bandwidth has been left for the non real time communication (e.g. based on IP and TCP) that can coexist on the same physical network. It should be noticed that in complex systems a complete bus cycle could be composed of several repetitions of RT, acyclic RT and non-RT data messages.

However within PROFINET IO RT, stations are not synchronized among each other; the cycle starts at different moments from station to station. Moreover standard switches can be employed with unpredictable results in terms of latency (i.e. a quite high jitter). In order to limit such phenomena, PROFINET IO RT specifications require that at least 40% of the bandwidth must left free of any kind of traffic. Recently, the validity of this approach in case of relaxed RT constrains has been shown by means of simulations [18].

As reported in [19], data exchange between an IO-Controller and an IO-Device is possible only if an Application Relation (AR) between them has been created during the setup phase. Using this AR an IO-Controller can cyclically read inputs and write outputs, receive acyclic alarms and acyclically read or write data (diagnosis data).

Inside an AR many Communication Relations (CRs) can be created as shown in Fig. 4. Acyclic CRs are used for exchange of parameters and configuration and operate on a client/server model (IO-controller=client, IO-Device=server).

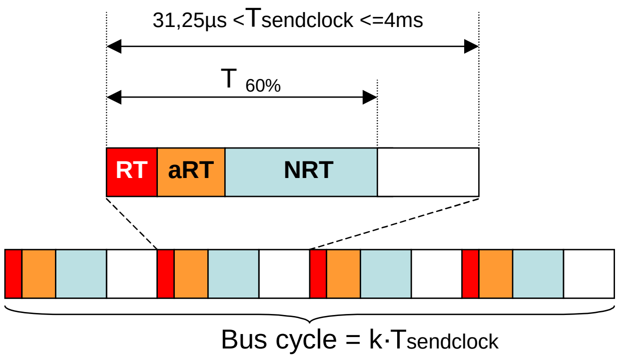

Fig. 3. A cycle in PROFINET IO RT. k is an integer multipling Tsendclock. (RT= Real-time communication, aRT= Acyclic real-time communication, NRT= non real-time communication).

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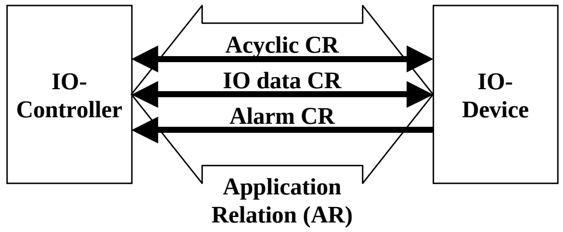

Fig. 4. In PROFINET IO the communication is structured by means of Application Relations that bundle several Communication Relations

I/O CRs transfer inputs and outputs data cyclically using a producer/consumer model with no acknowledge. Alarm CRs are used to notify events and alarms with a producer/consumer model with acknowledge.

It is important to say that a usual application with data to be exchanged bidirectionally requires two CRs, where the IO-Controller is the producer for the "IO-Controller to IO-Device" direction and the IO-Device is the producer for the "IO-Device to IO-Controller" direction. As previously described, PROFINET IO RT communication cycles in these devices are unsynchronized, thus typically no relations exist between time instants at which inputs or outputs are transmitted on the network.

Today, PROFINET IO Class 1 available products (e.g. from SIEMENS and Phoenix Contact) are principally dedicated to the distributed I/O field in industrial automation. Typically, cycle times involved in existing PROFINET IO applications are in the order of few milliseconds (from 1 ms to 20 ms). The release of PROFINET IO Class 3 IRT products, with tidily synchronized operation capability, is expected for the fist quarter of 2006.

4 Experimental Results

4.1 Experimental setup

A PROFIBUS/PROFINET test bench is currently available at the University of Brescia to experimentally evaluate timing performances of these fieldbuses. Such test plant can be upgraded or reconfigured every time a new experiment must be executed.

4.1.1 First test bench

The aim of the first experiment is to make a straight comparison between a PROFIBUS DP system and a PROFINET system. For such a reason the test network, shown in Fig. 5 has been kept as simple as possible.

A single PLC [20] has been used to alternately control both a PROFIBUS DP segment and a PROFINET IO network. Two identical slaves [21, 22], which differ only by the network interface, have been employed. The Ethernet segment requires the usage of a switch [23]; this switch is a "store&forward" industrial-category switch.

This symmetric setup allows experiments to be easily migrated from PROFIBUS to PROFINET. However, during a test only a network interface is initialized and active in the PLC, the other is left inactive.

It should be remarked that Application and PLL synchronization features of PROFIBUS DP V2 have been disabled in order to guarantee a fair comparison with PROFINET IO Class 1 devices that do not support isochrony.

4.1.2 Second test bench

The aim of the second experiment setup is to verify PROFINET IO Class 1 performances using devices from different vendors. The first PROFINET IO system is the same as presented before, whereas the new PROFINET IO system is composed of a PLC [24], a switch [25] and a slave [26] of a different manufacturer. The network topology, shown in Fig. 6, is the same as above.

4.1.3 Connection of measuring instruments

During the test a laboratory grade frequency meter [27] has been used to measure time intervals. Note that programmable width filters on digital inputs and outputs have been disabled in the slaves.

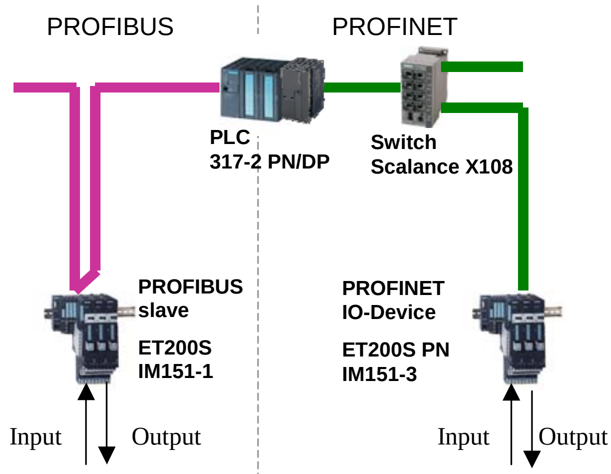

Fig. 5. Block diagram of the PROFIBUS DP and PROFINET IO Class 1 test networks

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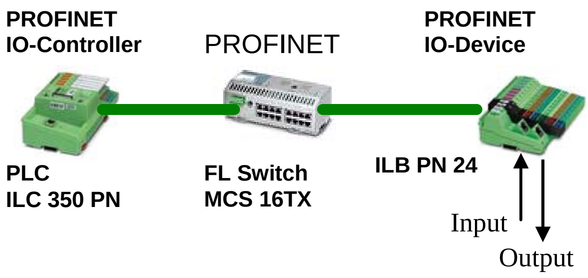

Fig. 6. Block diagram of the alternative PROFINET IO Class 1 test network

In order to verify traffic behavior directly at physical level an access to the bus is needed: a PROFIBUS analyser (Profitrace [28]) and an Ethernet sniffer (Ethereal [29]) based on a PC have been used. Fig. 7 illustrates insertion scheme for the two instruments. PROFIBUS analyser has been connected to the network as a node, since no stubs are allowed when operating at 12Mbit/s.

In PROFINET, IO-Controller and IO-Device require a full duplex connection otherwise they cannot go "on line". This constrain implies the usage of two (identical) switches and one hub [30] to connect the PC with the sniffer software. The configuration introduces an additional delay and jitter in the network, but this effect can be neglected since the network traffic is very low and is composed of small-size packets.

4.2 Results

The following results have been obtained using the first test bench.

The objective of the first experiment was to determine the distribution of the communication bus cycle duration T_{bus}. The measures have been obtained using the bus analysers described in the previous subsection. Table 1 shows average values of the bus cycle (1000 measures) and their standard

	Average T_{bus}[μs]	Std. Dev. [μs]	T_{bus} Max [μs]	T_{bus} Min [μs]
PROFIBUS DP V2	1000	1	1002	999
PROFINET IO-Controller	1000	19	1062	870
PROFINET IO-Device	1001	13	1184	820

Table1. Real bus cycle duration when T_{bus} = 1 ms is imposed. (PROFIBUS DP @ 12 Mbit/s, PROFINET IO @ 100 Mbit/s)

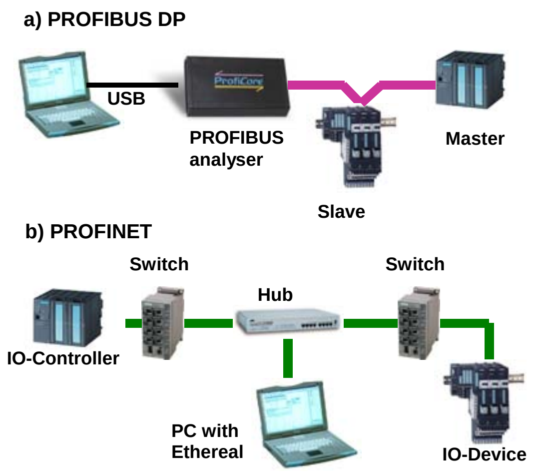

Fig. 7. Insertion diagram for the PROFIBUS DP analyser (a) and for the Ethernet sniffer (b).

deviations, in case of a very short bus cycle (T_{bus}=1 ms). For the PROFINET IO part of the experiment two results are reported since, as mentioned in the previous section, two bus cycles exist ("IO-Controller to IO-Device" direction and vice versa). The average value was expected to be extremely precise thanks to simplicity of the test network. However PROFIBUS DP V2 has a very regular behaviour whereas PROFINET IO RT has a larger distribution.

The aim of the next experiment was to evaluate the time required for information (a Boolean value) to circulate through the whole network. We called such time Event Reaction Time. Hence, the Master (IO-Controller) has been programmed to read the remote input of the Slave (IO-Device) and write back the inverted value on the remote output:

$$\text{Output} = \text{NEG (Input)} \quad (1).$$

On the other side of the network, at the slave side, input and output have been linked together. This "inverted loopback" generates a square wave signal on the slave output S_O as shown in Fig. 8. The Event Reaction Time is equivalent to the time T_H the signal S_O remains high.

Within PROFIBUS DP V2, if the master completes communication and processing tasks in less than T_{bus}, the time T_H is close to $2 \cdot T_{bus}$. In details, the time T_H is a multiple of the slave internal cycle duration T_{slave} , because the physical Output is driven by the slave. Effects of the quantization are shown in Fig. 9 for T_{bus} = 8 ms: two groups of points are visible, each one with its center value (T_{Hsx} and T_{Hdx}) and standard deviations (σ_{sx} and σ_{dx}).

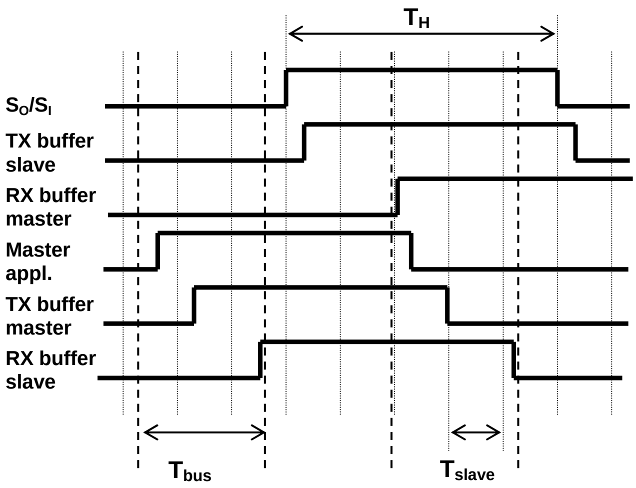

Fig. 8. Diagram of the signals that are generated when the slave output (S_O) is connected to the slave input (S_I).

The two peaks are not an exact multiple of T_{slave} due to: duration and asymmetry of rise and falling times in the slave; threshold below 50% in the frequency meter associated with the unavoidable slave output capacitance. T_{slave} can be calculated as the difference between T_{Hsx} and T_{Hdx} . Table 2 reports all the results obtained setting T_{bus} at 1, 2, 4, 8, 16, e 32 ms and acquiring 200 samples. With T_{bus}=1ms, two peaks are not clearly evident.

In PROFINET IO Class 1 data exchange is achieved in full duplex with two identical bus cycles of duration T_{bus}. These cycles are independent and not synchronized. T_H can assume values close to T_{bus} or $2 \cdot T_{bus}$ or $3 \cdot T_{bus}$, as the phase delay between the cycles shifts and becomes greater than T_{slave} and Master elaboration time. Fig. 10 shows results for T_{bus} = 8 ms and Table 3 summarizes experimental results (in terms of mean value T_{Hn} and standard deviation of each group σ_{Hn}) obtained setting T_{bus} at 1, 2, 4, 8, 16, e 32 ms and acquiring 200 samples. The PROFINET IO devices used in this paper implement the Class 1 protocol stack in software, resulting in smoothed distributions (e.g Fig. 10) of measures, where effect of quantization is less visible.

A comparison between the two implementations can be done after excluding fast cycles, where field devices reveal problems related to non ideality. In other words, network behavior can be predicted only if T_{bus} is greater than a certain threshold.

In industrial applications the main concern is the jitter that effects T_H. The results show that a PROFIBUS DP V2 system is more deterministic than a PROFINET IO Class 1 system. PROFINET IO Class 1 has an intrinsic jitter of T_{bus} due to unsynchronized input and output cycles, whereas PROFIBUS DP V2 exhibits a jitter equal to T_{slave}.

T_{bus}	PROFIBUS DP V2				
	T_{Hsx} [ms]	σ_{sx} [ms]	T_{Hdx} [ms]	σ_{dx} [ms]	T_{slave} [ms]
1 ms	2.310	0.137	3.026	0.067	-
2 ms	3.942	0.001	4.251	0.001	0.309
4 ms	7.968	0.001	8.278	0.001	0.309
8 ms	16.037	0.050	16.338	0.028	0.301
16 ms	32.147	0.008	32.456	0.029	0.308
32 ms	64.052	0.025	64.368	0.031	0.317

Table 2. Event Reaction Time T_H in PROFIBUS DP V2 varing T_{bus}. T_H is quantized with a step equal to T_{slave}.

T_{bus}	PROFINET IO Class 1					
	T_{H1} [ms]	σ_{H1} [ms]	T_{H2} [ms]	σ_{H2} [ms]	T_{H3} [ms]	σ_{H3} [ms]
1 ms	2.810	0.182	5.364	0.185	7.840	0.343
2 ms	4.556	0.427	6.626	0.170	8.834	0.182
4 ms	4.196	0.127	8.113	0.327	12.054	0.445
8 ms	8.187	0.714	16.051	0.732	-	-
16 ms	16.159	0.902	32.048	0.029	-	-
32 ms	32.208	0.540	64.017	0.359	-	-

Table 3. Event Reaction Time T_H in PROFINET IO Class 1 varing T_{bus}. T_H is quantized with a step equal to T_{bus}.

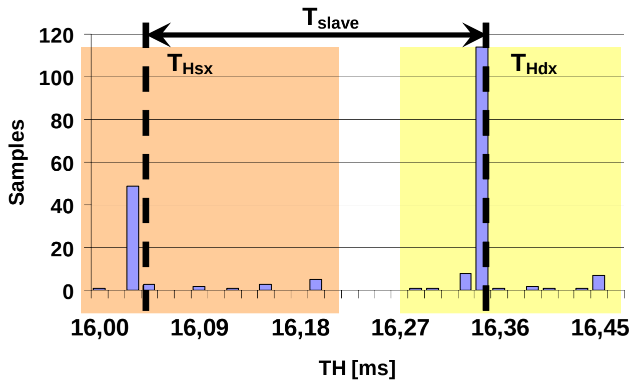

Fig. 9. Distribution of the T_H measurements in case of PROFIBUS DP V2 @12 Mbit/s with bus cycle T_{bus} = 8 ms. (200 samples).

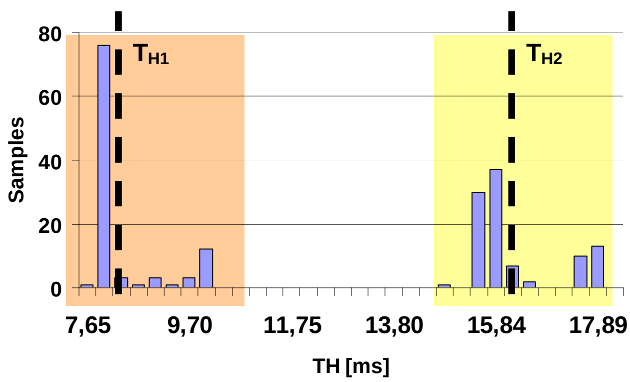

Fig. 10. Distribution of the T_H measurements in case of PROFIBUS IO Class 1 @100 Mbit/s with bus cycle T_{bus}=8 ms. (200 samples).

Last, a further experiment has been done using the second test bench. The aim is to evaluate real-time behavior of a different PROFINET IO Class 1 system. The comparison has been realized setting T_{bus} = 8 ms and the T_H measurement distribution is reported in Fig. 11.

This experimental setup gives better results in terms of standard deviation ($\sigma_{H1} \cong \sigma_{H2} \cong 60\mu s$) that leads to samples concentration within a narrow band centered in T_{H1} and T_{H2}. However, a gap still remains between such results and the PROFIBUS DP V2 case.

5 Conclusion

The need of fast networks for the industrial automation is growing. Solutions based on standard fieldbuses can achieve today objectives, but could fail tomorrow targets. Moreover, an integrated management even in big plants can lead to significant saving of money; system engineering and diagnostic should be transparently integrated into fieldbus technologies. Ethernet offers a great opportunity of realizing this vision, thanks to its low-cost, high-bandwidth and openness to well known protocols (IP and TCP).

A new Ethernet-based fieldbus, PROFINET IO, has been considered in this paper, comparing its performance with a traditional fieldbus as PROFIBUS DP V2. The performances of a simple automation application have been evaluated under the hypothesis of equal communication cycles.

In conclusion, PROFIBUS DP exhibits a better deterministic behavior than PROFINET IO Class 1. Actually, the jitter of the Event Reaction Time in a PROFINET IO Class 1 system is in the order of a bus cycle, whereas in a PROFIBUS DP V2 system the jitter is limited to the internal cycle time of the slave.

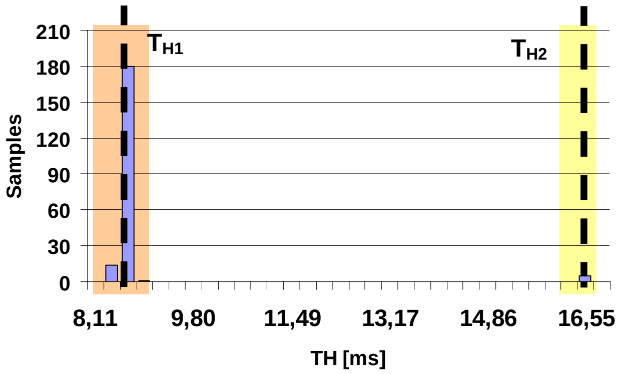

Fig. 11. Distribution of the T_H measurements when using the second test bench with PROFIBUS IO Class 1 @100 Mbit/s and bus cycle T_{bus}=8 ms. (200 samples).

In order to overcame this limit when time-critical isochronous applications are required, PROFINET IO Class 3 (IRT) has been announced.

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