Experimental analysis to estimate jitter in PROFINET IO Class 1 networks

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Abstract

This paper deals with Real-Time Ethernet networks based on PROFINET IO Class 1. Generally, industrial automation has a cyclical behavior; jitter in the application cycle depends on many factors and has direct consequences on production quality. In this work, in order to simplify application jitter estimation of complex systems, measurement techniques are introduced and some initial experiments on real devices are presented. Particularly, methods to experimentally estimate the cycle time of bus, IO-Controller and IO-Devices are proposed. Last, some analytical relations have been obtained: preliminary results show an estimation error less than 5%.

1. Introduction

Ethernet is the natural physical layer of more used protocols (first of all TCP/IP), including several high level protocols for industrial automation. 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. Some solutions are emerging, called Real Time Ethernet (RTE), as PROFINET IO, EtherCAT, Ethernet/IP, MODBUS-RTPS [1]. These technologies allow higher performances if compared to traditional fieldbuses and they will be included in the IEC61784-2 to be released in 2007. Real performance (e.g. jitter) estimation at application layer in a complex RTE system is a big issue, mainly because proposed protocols are new and still partially under development. This is also the case of the PROFINET communication profile family [2].

The aim of our long-term project is to obtain a method to estimate jitter and performance of a PROFINET IO Class 1 network starting from the model of real-time behavior of each network component. Generally, measurements on a single device are simpler than overall network performance estimation, thus the desired method could lead to quicker evaluations. In addition, components parameters, which are experimentally estimated, can be used to feed PROFINET IO Class 1 network simulators, speeding up development of new networks.

In this work the basic experimental measurement techniques and some analytical relations regarding real devices are described.

2. PROFINET IO network basics

PROFINET family includes PROFINET CBA, defined in IEC61784-1 as the CP 3/3, and PROFINET IO, to be defined in IEC61784-2 with CP 3/4, CP 3/5 and CP 3/6. Object of this work is PROFINET IO Class 1 (the future CP 3/4). A brief overview of its characteristics must be given before introducing experimental work [3, 4].

PROFINET IO identifies IO-Controllers, the intelligent devices which carry out automation tasks; IO-Devices, the devices that act as interface between the automation systems and the field (sensors, actuators, IO module etc.); and IO-Supervisors, for configuration and diagnosis purposes. A real-time communication channel shall exist between IO-Controllers and IO-Devices to exchange process data. Any other relations can be carried out using non-critical channel (i.e. UDP/IP). Classes in PROFINET IO define real-time behavior of systems: Class 1 and Class 2 are used in systems requiring cycle time of tenth of milliseconds; Class 3 can be used also when applications require cycle time down to few hundreds of microseconds and a strict isochrony. The release of PROFINET IO Class 3 products, with synchronized operation capability, is expected to be in the second half of 2006. Class 2 differs from Class 1 only for using UDP encapsulation also for real-time data.

PROFINET IO Class 1 uses the bus in a cyclical way, with a scheduling sequence that is continuously repeated by each station of the network. A cycle begins with transmission of real-time data between stations (process data first, then alarm data), followed by a portion of bandwidth that is free for the non real time communication (e.g. based on IP). In this manner, real-time data and UDP or TCP traffic can coexist on the same physical network.

There are some limits in PROFINET IO Class 1:

- stations are not synchronized among each other;
- cycle duration relies on device local clock, so PROFINET stations do not begin bus cycles at the same time
- standard switches can be employed with unpredictable results in terms of latency (i.e.
increasing jitter). In order to limit such phenomena, PROFINET IO RT specifications [5] require that at least 40% of the bandwidth must be free of any kind of traffic.

The main consequence of such limitations is that typically no relation exists among stations as regards time at which inputs or outputs are transmitted or received on the network.

3. The Proposed Approach

Fig. 1 illustrates long-term project flow: the first step is the isolation of any single contribution to global behavior, then device models will be proposed and a suitable methodology will be applied to estimate jitter and performance of the original complex system. Following sections regard the first phase with descriptions of measurements on single network devices and analytical relations among parameters.

4. Device Characterization

4.1. Test setup

A PROFINET IO demo network has been used, varying its configuration according to experiments. The test bench has been realized with currently available components [6, 7] as illustrated in Fig. 2. As a first approximation, effects of the switch device can be ignored since network traffic is low in our experiment. Moreover, I/O module configuration of PROFINET IO-Devices has been kept constant in these preliminary experiments. Time measurements have been carried out with a counter HP53131 A.

4.2. Output signal quantization

Generally timing characteristic of a complex system are studied on the basis of bus cycle, but in a real system the signals are generated by output drivers, both in the IO-controller and in IO-Devices. Thus, electrical and timing properties of these signals depend on output stage characteristic. The main effect of this constrain is on time intervals measured on real output that are always a multiple of the output refresh cycle. For instance, this quantization effect is related to PLC internal cycle in the IO-controller (local output) or to the slave internal cycle in the IO-Device (remote output). Anyway, the quantization effect is observable in all the following experiments.

4.3. IO-Controller (PLC) cycle time estimation

In a PROFINET IO Class 1 system the program execution cycle $T_{IOC}$ of an IO-Controller (i.e. the PLC) is generally not synchronized with the communication cycle. Process related data transported by PROFINET are read and written directly from and to the process images of the PLC. Duration and variability of the IO-controller cycle is expected to influence the global behavior, and it has to be estimated.

The experiment (see Fig. 2) has been carried out by means of a simple PLC program that only continuously commutes the local output $O_C$ (other signals unused). The waveform on $O_C$ is a square wave with period $2T_{IOC}$ as illustrated in Fig. 3. The relations

\[ T_{HI} = -T_{EC} + T_{IOC} + T_{IC} \]  
\[ T_{LI} = +T_{EC} + T_{IOC} - T_{IC} \]

express the time duration of the high level $T_{HI}$ and the low level $T_{LI}$ of $O_C$ signal, depending on output delay times ($T_{EC}$ on rising edge and $T_{IC}$ on falling edge) of PLC output module. $T_{IOC}$ can be derived from Eq. 3 if $T_{HI}$ and $T_{LI}$ are measured

\[ T_{IOC} = (T_{HI} + T_{LI}) / 2 \]

A typical distribution of $T_{HI}$ measurements is given in Fig. 4 when no IO-Devices are configured; distribution of $T_{LI}$ is similar. Several groups of samples are visible; their distance is quite constant (about 30 µs), probably indicating the PLC internal scheduling time. Asymmetry between rising delay and falling delay can be estimated using Eq. 4:

\[ (T_{f,C} – T_{r,C}) = (T_{HI} – T_{LI}) / 2 \]

Table 1 reports the estimate of $T_{IOC}$ in a network with 0, 1, 2 or 3 IO-Devices, obtained using the mean value of first group of measures as the best estimate of $T_{HI}$ and $T_{LI}$. $T_{IOC}$ value seems to increase linearly with number $N_{IOD}$ of configured IO-Devices:

\[ T_{IOC} = \alpha + \beta \cdot N_{IOD} \]

With the simple PLC program of our experiments

![Fig. 2. PROFINET IO Class 1 test network.](image)

![Fig. 3. Relation between $T_{IOC}$ and externally visible timing on output $O_C$.](image)
\(\alpha = 117 \, \mu\text{s} \) and \(\beta \approx 70 \, \mu\text{s}\). Generally speaking, in a real situation with a true PLC program and a generic number \(N_{\text{IOD}}\) of IO-Devices time, offset \(\alpha\) (which depends on running application) and slope \(\beta\) (which is almost independent from application) can be estimated, for instance, modifying the PLC program to include the continuous commutation of a PLC local output. Measures has to be taken, at least, for \(N_{\text{IOD}}\) and \(N_{\text{IOD}}+1\).

Output module asymmetry depends on exponential nature of real edges: time constant is short for rising edge and quite long for falling edge. Asymmetry increases when \(T_{\text{IOC}}\) increases, since a longer commutation period allows output to complete exponential grow and decay, while a fixed threshold is used in the counter.

### 4.4. Bus cycle time estimation

To evaluate the real cycle time of the PROFINET IO Class 1 channel the local output \(O_C\) of the IO-Controller has been connected to the remote input \(I_{D1}\) of the IO-Device 1 (ET 200S). The PLC program complements value of \(I_{D1}\) and writes it on \(O_C\). High level time \(T_{H2}\) and low level time \(T_{L2}\) of the square wave on \(O_C\) can be expressed by

\[
T_{H2} = -T_{r,C} + T_{PNq,C} + T_{f,C} \tag{6}
\]

\[
T_{L2} = +T_{r,C} + T_{PNq,C} - T_{f,C} \tag{7}
\]

where \(T_{PNq,C}\) is the quantized value of the time interval \(T_{PN}\) set in PROFINET IO configuration as bus cycle (aka refresh time). As described in section 4.2, in this case the output is driven by the PLC, so \(T_{PNq,C} = K \cdot T_{IOC}\) is expected, where \(K\) is an integer.

\(T_{PNq}\) and asymmetry have been obtained combining \(T_{H2}\) and \(T_{L2}\) as in section 4.3. In Fig. 5 the time \(T_{H2}\) is shown when only IO-Device 1 is configured: the PROFINET IO cycle time has been imposed to 16 ms and two groups of samples are visible. Distribution of \(T_{L2}\) samples is similar.

### 4.5. IO-Device cycle time estimation

The internal cycle time of an IO-Device can be evaluated connecting, for instance, the local input \(I_C\) of the IO-Controller with the remote output \(O_{Dx}\) of the IO-Device \(x\). If a PLC program complements the input \(I_C\) and writes the result to \(O_{Dx}\) a square wave is generated. In this case the signal is driven by the IO-Device and the following relations are valid

\[
T_{H3} = -T_{r,Dx} + T_{PNq,Dx} + T_{f,Dx} \tag{8}
\]

\[
T_{L3} = +T_{r,Dx} + T_{PNq,Dx} - T_{f,Dx} \tag{9}
\]

where \(T_{PNq,Dx} = M \cdot T_{IOD_x}\) is the quantized value of \(T_{PN}\); the quantization step is the internal cycle time \(T_{IOD_x}\) of the considered IO-Device. Summing and subtracting Eq. 8 and Eq. 9 leads to estimate \(T_{PNq,Dx}\) and asymmetry.

The distribution of \(T_{H3}\), when IO-Device 2 (ILB-PN24) is used and \(T_{PN}=16\) ms is imposed, is illustrated in Fig. 6 and it is similar to distribution of \(T_{L3}\). Two groups of samples can be isolated and processed as in section 4.4 to get the two quantized values of \(T_{PN}\).

Since two groups of samples are available, two \(T_{PNq}\) estimations are obtained: \(T_{PNq1,C}\) (group 1, lower approximation of \(T_{PNq,C}\)) and \(T_{PNq2,C}\) (group 2, higher approximation of \(T_{PNq,C}\)). As a verification, evaluation of \(T_{IOC}\) is also possible since \(T_{IOC} = T_{PNq2,C} - T_{PNq1,C}\).

Results are collected in Table 2 in case of two different IO-Devices D1 and D2. A general accordance between the prediction and real data can be noticed, with \(K\) that is close to an integer value. However, a slight discrepancy between \(T_{IOC}\) measured in section 4.3 in case of one IO-Device (187 µs) and \(T_{IOC}\) obtained in this section, is present. Relative error is in the order of 5% (10 µs) and it could be explained considering a different PLC program and changed asymmetry conditions.

<table>
<thead>
<tr>
<th>Table 1. IO-Controller cycle time (T_{IOC}) and output asymmetry.</th>
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<tbody>
<tr>
<td># IO-Device</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
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<table>
<thead>
<tr>
<th>Table 2. (T_{PNq,C}), (T_{IOC}) and asymmetry with two different IO-Devices .</th>
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<tbody>
<tr>
<td>IO-Dv</td>
</tr>
<tr>
<td>D1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>D2</td>
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Difference between $T_{PNq1,D2}$ and $T_{PNq2,D2}$ gives the $T_{IOD2}$ value reported in Table 3 according to Eq. 10:

$$T_{IOD2} = T_{PNq2,D2} - T_{PNq1,D2} \quad (10).$$

The listed results confirm the model, signalling an increased asymmetry due to the different output driver.

When IO-Device 1 (ET200S) is considered, the distribution of measurement samples of $T_{H3}$ is shown in Fig. 7: a more complicated situation is visible, since up to 6 groups can be isolated. It seems that two independent cycles run inside IO-Device 1; for instance, one process to manage the PROFINET interface and another one to refresh outputs. The effect of such a kind of double quantization can be simplified and expressed by:

$$T_{PNq,D1} = M \cdot T_{IOD1} + N \cdot t_{IOD1} \quad \text{with } N \in \{-1, 0, 1\} \quad (11)$$

where $t_{IOD1}$ is the duration of the shortest internal process and $M$ is an integer.

Looking at Fig. 7, the following relations can be deduced:

$$T_{IOD1} = T_{PNq4,D1} - T_{PNq1,D1} \quad (12)$$

$$T_{IOD1} = T_{PNq5,D1} - T_{PNq2,D1} \quad (13)$$

$$T_{IOD1} = T_{PNq6,D1} - T_{PNq3,D1} \quad (14)$$

$$t_{IOD1} = T_{PNq2,D1} - T_{PNq1,D1} \quad (15)$$

$$t_{IOD1} = T_{PNq3,D1} - T_{PNq2,D1} \quad (16)$$

$$t_{IOD1} = T_{PNq5,D1} - T_{PNq4,D1} \quad (17)$$

$$t_{IOD1} = T_{PNq6,D1} - T_{PNq5,D1} \quad (18)$$

Table 4 shows the real results obtained and a general agreement with the proposed model is noticeable: value of $M$ are very close to an integer. Few samples are in group 6, so estimation uncertainty increases if group 6 is considered.

To sum up, modeling of a IO-Device is not trivial as it strongly depends on internal implementation, i.e. on manufactures. Simple relations in Eq. 10 and 11 must be expanded to consider the number of I/O modules.

5. Future work

The first step of our long-term project has been completed. Generally, agreement between proposed relations and measurements are very good with an error below 5%. The future work will be the validation of existing relations using more complex test systems. Then, implementation of jitter estimation models using OPNET will be done, followed by test on real systems.

References


[6] SIEMENS CPU317 PN/DP-2 model # 6ES7 317-2EJ10-0AB0, ET200S PN model # 6ES7 151-3AA00-0AB, Scalance X208 model # 6GK5 208-0BA00-2AA3, manuals at http://mall.automation.siemens.com

[7] Phoenix Contact ILB PN 24, model #2878146, FL IL 24 BK-PN model #2878816, manuals at http://www.phoenixcontact.com