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Timeliness in COTS Factory-Floor Distributed Systems: What Role for Simulation?

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Abstract:
Throughout the years, researchers have developed and applied a considerable range of theory to the validation of factory-floor distributed real-time systems. In the past few years, it is particularly significant the considerable amount of work that has been devoted to the timing analysis of Ethernet-based technologies. It happens, however, that the majority of those works are restricted to the analysis of sub-sets of the overall computing and communication system, thus without addressing timeliness at a holistic level. In this paper we describe a research framework that is being set-up to embrace this objective.

It is known that analytical models to provide real-time guarantees for factory-floor distributed systems, such as those based on worst-case scenarios tend to be overwhelmed with simplifications that often lead to very pessimistic assumptions, and therefore very pessimistic results. In this paper we advocate that discrete event simulation models of a distributed system can be a powerful tool, not only for the timeliness evaluation of the overall system, but also to provide results enabling less pessimistic assumptions for the analytical response time approach. To this end, we address a few inter-linked research topics with the purpose of setting a framework for the development of tools suitable to extract temporal properties of Commercial-Off-The-Shelf (COTS) factory-floor communication systems. In order to consolidate some of the ideas and exemplify some of the concerns outlined throughout the paper, a specific COTS technology, Ethernet/IP, is brought into the discussions.

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Abstract

Throughout the years, researchers have developed and applied a considerable range of theory to the validation of factory-floor distributed real-time systems. In the past few years, it is particularly significant the considerable amount of work that has been devoted to the timing analysis of Ethernet-based technologies. It happens, however, that the majority of those works are restricted to the analysis of sub-sets of the overall computing and communication system, thus without addressing timeliness at a holistic level. In this paper we describe a research framework that is being set-up to embrace this objective.

It is known that analytical models to provide real-time guarantees for factory-floor distributed systems, such as those based on worst-case scenarios tend to be overwhelmed with simplifications that often lead to very pessimistic assumptions, and therefore very pessimistic results. In this paper we advocate that discrete event simulation models of a distributed system can be a powerful tool, not only for the timeliness evaluation of the overall system, but also to provide results enabling less pessimistic assumptions for the analytical response time approach. To this end, we address a few inter-linked research topics with the purpose of setting a framework for the development of tools suitable to extract temporal properties of Commercial-Off-The-Shelf (COTS) factory-floor communication systems. In order to consolidate some of the ideas and exemplify some of the concerns outlined throughout the paper, a specific COTS technology, Ethernet/IP, is brought into the discussions.

1. Motivation

The factory-floor has been, since a few decades now, one of the major application environments for real-time distributed computing systems [1]. In such environments, applications must be devised and deployed such as timing constraints are fulfilled, thus guaranteeing the correct behaviour of the overall system. To meet these requirements, systems are built using appropriate allocation techniques and predictable scheduling algorithms, for both tasks and related communicating message streams.

This deterministic behaviour of the system is usually exploited in a framework dominated by the notion of absolute temporal guarantees. In those systems, computational and communication loads are presumed to be bounded and known, and the worst-case (at least believed to be) conditions are assumed. In this way, the problem of engineering distributed real-time systems, of which factory-floor distributed computing systems are a representative example, becomes a problem of devising the appropriate tools and methods to assure that all deadlines are met in all circumstances [2].

To this end, researchers usually follow two, usually alternative, approaches. These two approaches are based on:

1. simulation models of system components that mirror the actual behaviour of the system;
2. analytical models that give a measure of worst-case system latencies.

Each of those has advantages and disadvantages, when compared to each other. Simulation-based models can be applied to virtually all problems, and system details can be embodied into the models up to the desired level. However, a major drawback may turn out to be the time required in executing the simulation for large and realistic systems, particularly when results with high accuracy (narrow confidence intervals) are desired. Also, typically, simulations require the use of simulation development and deployment tools that entail difficulties or are not appropriate to be applied to the target system. These drawbacks do not exist to the same extent in analytical-based approaches. However, and for complex distributed systems, analytical-based models tend to be overwhelmed with simplifications that often lead to very pessimistic assumptions, and therefore to very pessimistic worst-case results. Even knowing that a number of existing techniques may potentially be used and adapted to reduce this pessimism level, the benefit may appear at the cost of adding rather complex abstractions, such as precedence relationships [3], event phasing [4, 5] and inheritance of time characteristics [6, 7]. These, unfortunately, may lead to intractable mathematical models, thus making it further difficult to handle and reason the analytical abstractions.

There is another concern that is important to bring into this context. In fact, although the deterministic framework has been proved valid for the deployment of real-time systems in a wide range of applications, it is now accepted that it may pose serious research challenges when trying to apply it to some other application areas. This is eventually the case of some distributed systems that are more flexible and adaptive in their nature. In this direction, a great amount of research is being performed towards including, into the traditional analytical models for computing worst-case response time, some stochastic representation of the events. Clearly, this may only be good to provide some form of probabilistic guarantees. However, there might be some useful results if the application can cope with occasional deadline misses, within some quantifiable limits [8-13].

A more recent work [14], introduced some concrete ideas for the development of a framework were the traditional response-time analysis of tasks scheduled in a single processor environment according to the rate monotonic policy [15] could potentially be extended to incorporate a probabilistic characterisation of task arrivals and execution times.

Although most of these works concentrate on particular aspects of the analytical models, and concern also particular targeted systems, they create the eagerness towards revisiting the problem of engineering Commercial-Off-The-Shelf (COTS) real-time factory-floor systems. However, in our view, a fundamental issue must always be given the most attention when trying to work in that direction. This issue relates to the problem of how to accurately describe, in statistical terms, a concrete COTS system (or sub-system)? The reason for highlighting this issue comes from the evidence (not always stated in related works) that the validity of the results and guarantees that can be provided are very much sensitive and dependent on the correct statistical characterisation of the system, for instance by means of probability distribution functions. This depends on the concrete system and on the concrete application of the system. In this paper, we advocate a research framework in which discrete event simulation models of a distributed system is combined with the more traditional (at least in the real-time systems community) analytical response time analysis. In such a framework, simulation can play an important role, not only for the timeliness evaluation of the overall distributed system, but also in providing results enabling less pessimistic assumptions for the analytical response time approach. That is, simulation results can be used to introduce reasonable probabilistic assumptions into analytical models, or pave the way to efficiently reason about precedence and offsets of events. Thus digging on simulation approaches of systems may also enable profitable enhancements to analytical response time approaches to better reflect the timing properties of the system under evaluation.

To this end, in this paper we address a few inter-linked research topics that we have been carrying out with the purpose of extracting temporal properties of COTS factory-floor communication systems. The concrete example of COTS technology that is brought to the discussions is Ethernet/IP [16, 17]. This technology is briefly described in Section 2. In Section 3, we outline a simple worst-case end-to-end response time analytical approach. The outlined approach has no claims of being an elaborated or pessimistic-reduced approach. The purpose is to give, later on in the paper, a rough measure of the pessimism contained in such type of approaches that potentially worthies further refinement and research effort. In Section 4, we describe how we have been tackling the problem of simulating distributed systems based on the same COTS technology. Evaluation of worst-case response time is given for the same scenarios used in Section 3, which leads the flow of the paper to a discussion of the results in Section 5. In this section, we reinforce the baseline that motivates the prosecution of the inter-related research lines: exploiting discrete event simulation models, not only for the timeliness evaluation of the overall distributed real-time COTS system, but also to provide results enabling less pessimistic assumptions for the analytical response time approaches.

2. An Example COTS Technology: Ethernet/IP

Ethernet-based technologies have already gained a strong position in the factory-floor. For many years, deemed non-determinist, Ethernet has gone through some evolution which, even for the fundamentalists, enables its use in real-time applications [16, 18, 19].

Although lots of attention has been devoted to the timing analysis of Ethernet-like technologies and solutions, most of the work on Ethernet has been restricted to the Data Link Layer level. It is still to come an overall approach that allows the evaluation of a whole Ethernet-based distributed computing system, incorporating features above the Data Link Layer. The control community argues that Ethernet itself does not include any features above data link layer [20]. TCP/UDP/IP protocols can of course be used to fill up some of the layers above Ethernet. However, what about layers above the transport layer [20]? Moreover, which performance characteristics will be attained with the ensemble?

There are already some COTS solutions for Ethernet-based systems providing a fully defined communication protocol stack. One of such solutions, based on encapsulation technologies, is Ethernet/IP, where IP stands for “Industrial Protocol”. Ethernet/IP [17] is a communication system suitable for use in industrial environments and time-critical applications. It is an open industrial networking standard that takes advantage of commercial, off-the-shelf Ethernet communication chips and physical media. For the application, Ethernet/IP makes use of an open protocol named CIP (Control and Information Protocol). CIP is an Application layer protocol that implements a distributed object model, using the TCP/IP and UDP/IP services, and relies on multicast to provide Producer/Consumer services [17]. Time-critical data is periodically (defined by the Requested Packet Interval – RPI – parameter) exchanged using a producer/consumer model, based on multicast UDP/IP, which in turn is mapped on the Ethernet multicast service.

Ethernet/IP Networks are constituted of three basic elements: Remote I/Os, Controllers and interconnecting switches. These elements communicate with each other via Ethernet.

The Remote I/O and Controller nodes can be composed by a number of different modules communicating via a device-specific backplane (Figure 1). Typically, a Controller is composed of a number of I/O modules (labelled in the figure as *I* or *O*), several Controller modules (*C*) and one or more Ethernet Adapters (*EA*). A Remote I/O, although a simpler node, is similarly constituted, with exception for the Controller modules.

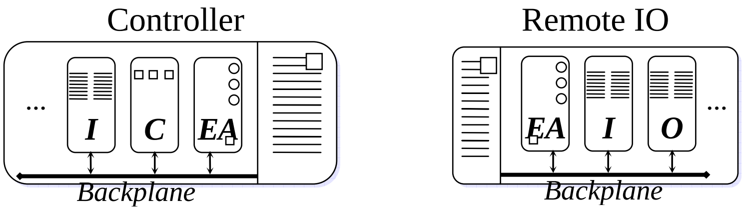

Figure 1. Ethernet/IP basic nodes.

3. Digging on Worst-Case Response Time Analysis for Ethernet/IP

An effort to formulate an analytical solution enabling to find end-to-end response times in Ethernet/IP based distributed systems is being performed, using the concept of attribute inherence [6, 7]. While this is a very interesting and useful approach to start with, it basically leads to an additive formulation built on top of several worst-case assumptions, thus potentially exacerbating the levels of pessimism. This level of pessimism is easily foreseen in a distributed system, where the probability of concurrence of independently generated worst-case situations is realistically extremely low. Nevertheless, later on in the paper we will see that the rough analytical proposal is not as pessimistic as would be expected. The justification comes from the time-triggered approach of the Ethernet/IP CIP, and the RPI based behaviour mentioned in the previous section.

Before presenting the (basic) analytical formulation for the worst-case end-to-end delay in Ethernet/IP transactions, a few words on assumptions are worthy to be provided.

We consider a number of components leading to the end-to-end transaction latency, illustrated for a simple transaction on a rather simple Ethernet/IP network in Figure 2.

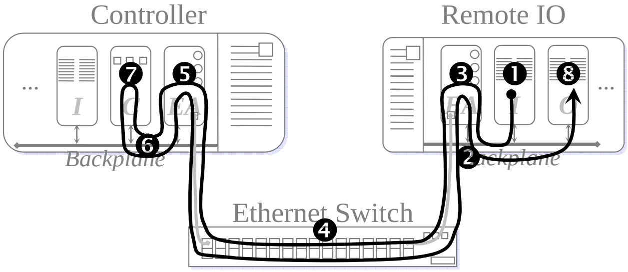

Figure 2. Major end-to-end delay components.

The transaction starts at the input module of the Remote I/O (①). After the hardware delay to energise the input and a user defined filter delay, a message with the input data will be generated, at the periodicity defined for the input data connection. This message will then suffer the contention caused by the device backplane (②), and will arrive at the Ethernet Adapter, where it is processed, encapsulated and transmitted via the Ethernet communication interface (③). With this, the message arrives at the Ethernet switch, where it is relayed to the corresponding output port(s), and later will arrive at the Controller Ethernet Adapter (④). At the Ethernet Adapter (⑤), the message is processed, in order to be passed to the Controller module, passing through the Controller backplane (⑥). At the controller the input data will be processed by a controller task, characterised by a worst-case response time, that generates the corresponding output data (⑦). The output data will be transmitted at a defined periodicity and will go back through the inverse path (⑥,⑤,④), until it reaches the Ethernet Adapter of the Remote I/O (③), is processed and delivered to the output module that will, in result, energise the corresponding output(s) (⑧).

3.1. Analytical Formulation of the Worst-Case End-to-End Latency

A rough analytical formulation for computing the worst-case end-to-end delay of a transaction could then be as follows (the reader is referred to [21] for a more complete characterisation and formulation):

$$R_i = fd + \sum_{j \in \{input, output\}} (As_j + Qs_j + Ao_j) + Rtask \qquad \textbf{(1)}$$

In this equation, *fd* is the user defined filter delay for the input data, which is added to the sum of the several components in both input and output direction. The worst-case time that a message takes, from the input data connection, to arrive at the intermediate switching device is defined by As_j. This component includes the periodicity associated with the data connection, backplane contention and queuing at the Controller's Ethernet Adapter. The queuing delay a message may encounter at the Ethernet switch is represented by Qs_j. Ao_j is the worst-case time that the message takes from the Ethernet switch to the output point, which may be the Controller task or the Remote I/O output. The controller device runs a set of tasks, defined by the user. The device schedules each task according to a fixed priority schedule (FPS) and the user assigns the priorities. Thus, it is possible to determine a worst-case response time for the task processing the input data (*Rtask*).

3.2. Numerical Examples

For the purpose of instantiating these calculations, a scenario with three end-to-end transactions, similar to the presented in Figure 2, was setup. Table 1 contains the parameters for these tree transactions, along with the response time of the Controller task processing the input data.

Description	*Value (ms)*
Input Filter values.	0
Periodicity of transaction 1	5
Periodicity of transaction 2.	7
Periodicity of transaction 3.	15
Response time calculated for task processing inputs of transactions 1, 2 and 3	3

Table 1. Timing parameters for three end-to-end data transactions.

In order to perform the necessary calculations, some additional, device-specific, information is required, which is included in Table 2, below.

Description	*Value (ms)*
Assumed worst-case processing delay in the Ethernet Adapter (per message)	0,20
Assumed worst-case switching delay (per message)	0,02
Assumed value of the time slot, (backplane medium access)	0,05

Table 2. Assumptions for device-specific parameters.

The values in Table 2 consist on the assumed worst-case delays, per message, in the Ethernet Adapter of each Ethernet/IP node and in the Ethernet Switch. Additionally, it is assumed a time slot for the backplane access medium, therefore considering this backplane as using a Time Division Multiple Access (TDMA) protocol.

Applying the analytical formulation to this scenario, enable us to reach the worst-case latencies as given in Table 3.

Transaction	*Analytical worst-case (ms)*	As_{input}	Qs_{input}	Ao_{input}	As_{output}	Qs_{output}	Ao_{output}
1	17,57	5,75	0,06	1,5	6,5	0,06	0,75
2	21,57	7,75	0,06	1,5	8,5	0,06	0,75
3	42,57	15,75	0,06	1,5	16,5	0,06	0,75

Table 3. Analytical worst-case results (scenario 1).

A more complex configuration scenario is illustrated in Figure 3, where 10 end-to-end transactions, with diverse periodicities are considered.

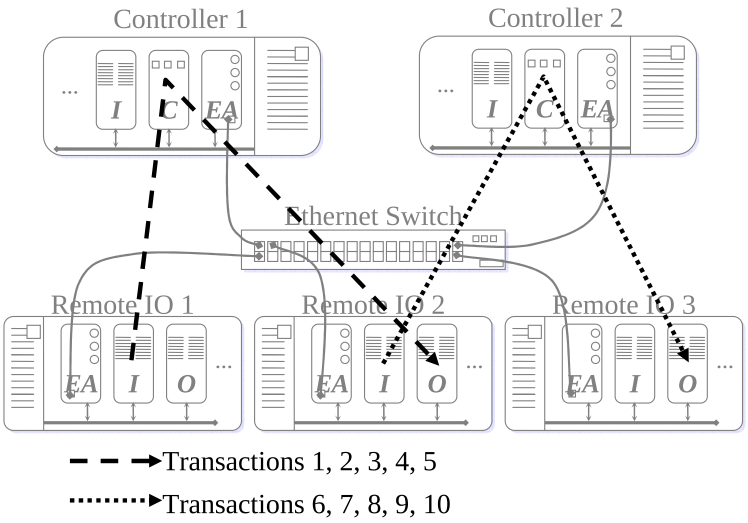

Figure 3. Example scenario (scenario 2) involving ten end-to-end transactions.

In this scenario, Controller 1 processes 5 inputs originated in Remote I/O 1, generating 5 corresponding outputs, delivered to Remote I/O 2. This latter Remote I/O generates 5 inputs, delivered and processed at Controller 2, which, in turn produces 5 outputs to be sent to Remote I/O 3. Table 4 lists the relevant timing parameters considered for this scenario.

Description	*Value (ms)*
Input Filter values.	0
Periodicity of transaction 1	10
Periodicity of transaction 2	23
Periodicity of transaction 3	7
Periodicity of transaction 4	12
Periodicity of transaction 5	75
Periodicity of transaction 6	11
Periodicity of transaction 7	19
Periodicity of transaction 8	5
Periodicity of transaction 9	21
Periodicity of transaction 10	15
Response time calculated for task processing inputs of transactions 1, 2, 3, 4, 5	3
Response time calculated for task processing inputs of transactions 6, 7, 8, 9, 10	3

Table 4. Parameters for ten end-to-end data transactions.

Applying the same procedure as for the previous example, it is possible to obtain the following end-to-end worst-case latencies (Table 2 still applies for this scenario).

Transaction	*Analytical worst-case (ms)*
1	32,05
2	58,05
3	26,05
4	36,05
5	162,05
6	33,95
7	49,95
8	21,95
9	53,95
10	41,95

Table 5. Analytical worst-case results (scenario 2).

4. Digging on Simulation of Ethernet/IP Networks

The problem of simulating distributed systems based on COTS technologies is being addressed, with the purpose of fostering the development of a combined analysis, where simulation enables less pessimistic assumptions for the analytical response time approach. Simulation is basically the imitation of the operation of a real-world system over time. The availability of special-purpose simulation languages, increasing computing capabilities at a decreasing cost per operation and advances in simulation methodologies, have made simulation one of the most accepted tools in operations research and systems analysis [22].

Simulation, for the study of any system, usually involves the development of a model, where the details and behaviour that affect the system under study are represented. Checking that the simulation model properly reflects the real-world system is made either by comparing simple observations of the system with the model, by conversation with system experts, by using existing theory and other relevant results, or using quantitative techniques (like distribution fitting, homogeneity tests or sensitivity analysis) to validate particular components [22].

A Ethernet/IP simulation environment was developed using the OMNeT++ [23] discrete event simulation platform. OMNeT++ is an object oriented modular discrete event simulator, which provides a reusable component framework, where the system components can be independently built and then characterised and assembled into larger components and models.

The use of COTS components in Ethernet/IP based systems is an important issue for the model validation, considering that this model may encompass equipment from different manufacturers, thus precluding the notion of a system-wide verification. This gives particular importance to the separate modelling of components at different levels of detail.

4.1. Simulation Model

Our simulation model is composed of three basic nodes: a Remote IO, a Controller and an Ethernet Switch. Each of these can be instantiated into several different device models, with different particular characteristics. These nodes are sufficiently modular and parameterized so that the simulation of any concrete Ethernet/IP system is feasible. Figure 4 depicts a simple network that includes the three basic nodes.

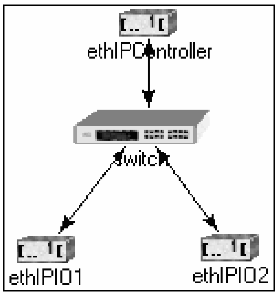

Figure 4. Ethernet/IP simulation network example.

As stated in Section 2, Ethernet/IP nodes can be composed of several modules. For instance, a Controller may be composed of several controller modules, several I/O modules and a communication interface, all communicating with each other via a device-specific backplane. Figure 5 portrays a possible configuration of a controller node.

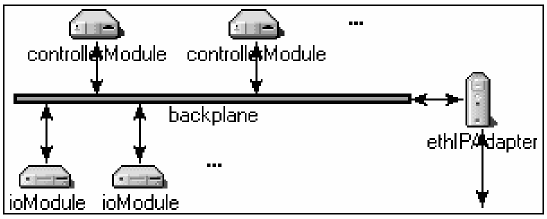

Figure 5. Ethernet/IP Controller node model example.

Each module of a node can be further refined with additional components, increasing the model’s level of detail. Noticeably, during the development of the simulation model, an effort was made to allow the details within each component to be refined if necessary (in an easy and safe way). It is important to incorporate in the models the appropriate level of detail, avoiding the introduction of superfluous features that can impair the simulation performance.

The development of several different models, at different levels of abstraction, possibly for different components of the system, allows first to consider each component in separate and then their integration. More detailed models provide inputs for more sustained assumptions into the simplified models. A similar approach may be applied to obtain proper statistical characterization of the system components and use it has input into an analytical approach.

A development process, such as the one described in the previous paragraph, introduces a modelling trade-off between simulation performance and level of detail. Drawing any type of conclusions using a simulation also brings forward the need for narrow confidence intervals, and, therefore, large amount of simulation data. For this reason, the performance of the simulation assumes a very important role. In fact, some experiments carried out with different models, incorporating diverse levels of detail have shown that the performance of the simulation is reduced by elevating the level of detail, particularly for increased complexity of the simulated system.

4.2. Numerical Example

In Section 3, we have described a simple worst-case end-to-end response time analytical approach for the concrete example of Ethernet/IP. In order to give a rough measure of the pessimism contained in such type of approaches, we will study the same example scenarios considering the worst-case end-to-end response time actually seen in the simulated model.

Considering the network typology and parameters depicted in Figure 2 and Tables 1 and 2, a long simulation run was performed allowing obtaining the results presented in Table 6.

Transaction	*Simulation worst-case (ms)*	*Average*	*Stdev for one sample*
1	10,49	7,88	1,44E-3
2	14,61	10,87	2,03E-3
3	30,55	23,01	4,38E-3

Table 6. Simulation worst-case calculation results (scenario 1).

Another simulation run was carried out for the second scenario (Figure 3). The results of the worst-case verified in this simulation run are included in table 7.

Transaction	*Simulation worst-case (ms)*	*Average*	*Stdev for one sample*
1	21,01	15,63	2,93E-3
2	47,05	35,35	2,93E-3
3	15,09	11,15	2,06E-3
4	25,00	18,63	3,53E-3
5	150,76	113,96	2,14E-3
6	22,86	17,15	3,21E-3
7	38,63	29,09	5,48E-3
8	10,80	8,03	1,46E-3
9	42,78	31,90	6,15E-3
10	30,89	22,96	4,35E-3

Table 7. Simulation worst-case calculation results (scenario 2).

The confidence intervals obtained from any simulation results also depend considerably on the variance of the data gathered. This variance depends on the nature of the data and of the system, but some statistical techniques may enable reducing the variance of an output random variable, without disturbing its probability [22].

A brief inspection of the variance obtained in the simulation runs performed allows verifying that the simulation has a satisfactory confidence interval (99,90%), and within an accuracy of 1 ms [24]. While the proper analysis of a simulation output requires more elaborate statistical techniques, in order to attain more correct conclusions, this simple analysis gives a rough idea of the expected characteristics of the output data.

Besides the previous note about the accuracy of such results, this might enable a measure about the distance between the worst-case of the analytical results and the average and worst-case that actually can be verified within a considerable life-time of the simulation.

5. Discussion

The discussion of these inter-linked research topics can be made by comparing the results of the analytical worst-case response time with the worst case verified during the simulation runs. Tables 8 and 9 present this comparison, for the two scenarios addressed within the previous sections.

Transaction	*Analytical worst-case (ms)*	*Simulation worst-case (ms)*	*Difference*
1	17,57	11,65	40%
2	21,57	15,58	32%
3	42,57	31,62	28%

Table 8. Results comparison (scenario 1).

Transaction	*Analytical worst-case (ms)*	*Simulation worst-case (ms)*	*Difference*
1	32,05	21,01	34%
2	58,05	47,05	19%
3	26,05	15,09	42%
4	36,05	25,00	31%
5	162,05	150,76	7%
6	33,95	22,86	33%
7	49,95	38,63	23%
8	21,95	10,80	51%
9	53,95	42,78	21%
10	41,95	30,89	26%

Table 9. Results comparison (scenario 2).

Considering these results, it is clear that the analytical formulation, based on a number of worst-case assumptions, presents pessimistic results. It is known that the simulation model only provides results at a certain level of confidence, derived from the variability of the model and of the length of a simulation run. Nevertheless, the distance between the worst-case of the analytical results and the worst-case (and average) that actually can be verified with the simulation is by itself significant. Even more important is the fact that as the system becomes more complex, the pessimism increases, thus increasing the necessity to consider a stochastic representation of the events.

The problem of developing methods to correctly introduce and handle probabilistic assumptions in analytical models has already been tackled by several researchers [8-13]. Nevertheless, even assuming the existence of a probabilistic characterisation of the system components, it is also clear that the correct characterisation, in statistical terms, of a system is very much sensitive and dependent on the concrete system and on the concrete application of the system. This characterization becomes a problem with greater relevance when the complexity of the system is increasingly higher and an *a priori* evaluation of the system is required. Additionally, the correct results of a probabilistic analysis are, in great magnitude, dependent on these inputs.

The use of discrete event simulation models is thus an appealing approach for the analysis of intricate systems. Being a very practical tool and because of its approximation to the real world, discrete-event simulation presents itself as an attractive method to acquire knowledge of elaborate distributed systems, recurring to the statistical background already quite developed for the analysis of simulation data.

It is therefore important to foster the emergence of a research framework combining the discrete event simulation models of a distributed system with the traditional real-time analytical response time analysis. In such a framework, results obtained through simulation can be used as feedback to better characterise the assumptions for the analytical response time approach. Simulation approaches may enable profitable enhancements to analytical response time approaches to better reflect the timing properties of the system under evaluation.

6. Conclusions

In this paper, a motivation is given to foster the extraction of overall temporal properties of COTS factory-floor communication systems through the combination of different, but potentially integrated, types of analysis. In a first approach, a concrete Ethernet-based COTS technology is used (Ethernet/IP), which provides a fully defined communication protocol stack. The paper outlines the major components of Ethernet/IP systems, identifying the major delay components in its distributed transactions.

This is then used to delineate a simple end-to-end worst-case analysis for Ethernet/IP based distributed systems. Although this analysis is used with the purpose of illustrating the inherent pessimism typically presented in such worst-case approaches, *per se* it contains a relevant contribution for the holistic analysis of Ethernet-based COTS systems.

In order to tackle the problem of pessimism in this type of analysis, a simulation model for the same technology is provided. This simulation model adds relevant considerations to the modelling of distributed systems, but importantly, the results obtained motivate a discussion to expose several inter-related lines of investigation, supporting a research framework in which discrete event simulation models of a distributed system are combined with the analytical response time analysis. Simulation can play an important role, not only for the timeliness evaluation of the overall distributed system, but also to provide results enabling less pessimistic assumptions for the analytical response time approach. Simulation results can be used to introduce reasonable probabilistic assumptions into analytical models, or allow the efficient characterisation of the diverse components of the system.

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