EUROPEAN COMMISSION

Thematic Priority:
SIXTH FRAMEWORK PROGRAM

Priority 2.5.3
INFORMATION SOCIETY TECHNOLOGIES
Unit G3 Embedded Systems

Project Acronym:

SOCRADES

Project Full Title:

Service-Oriented Cross-layer infRAstructure for Distributed smart Embedded devices

Proposal/Contract No: EU FP6 IST-5-034116 IP SOCRADES

Milestone 4.2
Simulation of control under uncertain sensor and actuator communication

Status:	Final
Dissemination Level:	CONFIDENTIAL
Date:	11.04.2008

Organization Name of the Lead Contractor for this Milestone: ABB

Status Description:

Scheduled completion date[1]:	11.04.2008	Actual completion date[2]:	11.04.2008
Short document description:	The paper provides description of reaching the Project Milestone M4.2. It comes as a companion to D4.1. and provides the support for 5. The responsibility for the generation the MS report was allocated to WP4.		
Author(s) deliverable:	Tiberiu Seceleanu (ABB) Alf Isaksson (ABB) Mauro De Biasi (ABB) Carlo Snickars (ABB)	**Report/deliverable classification:** [ ] Deliverable [X] Milestone Report [ ] Three-Monthly Activity Report [ ] Six-Monthly Activity Report	
Partner (Contributions / Peer reviews)	[ ] [ ] Schneider Electric [X] [X] ABB [ ] [ ] APS GmbH [ ] [ ] Boliden AB [ ] [ ] FlexLink Components AB [ ] [ ] Institut f. Automation und Kommunikation e.V. Magdeburg [ ] [X] Kungliga Tekniska Högskolan	[ ] [ ] Loughborough University [ ] [X] Luleå University of Technology [ ] [ ] Politecnico di Milano [ ] [X] SAP AG [ ] [ ] Siemens AG [ ] [ ] Tampere University of Technology [ ] [ ] Jaguar Cars Ltd. [ ] [ ] ARM Ltd.	
Peer review approval :	[X] Approved [ ] Rejected (improve as specified hereunder)	Date:	[28.03.2008]
Suggested improvements:			

[1] As defined in the DoW
[2] Scheduled date for approval

Table of Contents:

List of Figures:

1. Introduction

An automation system should be a **deterministic, secure and fault-tolerant system** of networked embedded devices, where diverse heterogeneous physical objects co-operate to achieve a given goal. Wireless devices become increasingly interesting since a growing part of the real cost is associated with the installation (wiring) of the devices.

However, not only is wireless communication sensitive to interference from background noise, but also to competing wireless networks. If wireless communication finds its way into industrial communication, which we believe, we must handle the situation where several different wireless networks will compete for the shared media. Possibly, new scheduling mechanisms need to be developed to handle the possible conflict and traffic congestion.

In order to find solutions to the plenitude of issues affecting the communication based on wireless protocols, we start by assessing in a non-intrusive manner, that is, by simulation, the possible effects of disturbances on communication content and timing on wireless connections. We proceed here by checking the following aspects:

- Generic sources of errors in wireless communication
- Modeling errors
- Analysis of the simulated models
- Scheduling communication

2. Roadmap for reaching milestone 4.2

2.1. Task 4.1

Task 4.1. started and finished as planned, executing in the interval M1 – M12.

The ultimate objective of task 4.1. was to propose an architecture for wireless communication, addressing communication *and* control strategies. The communication scheme in figure 1. can be said to present the most general case of wireless communication in a control system [1].

Basically, the issues to be answered in MS.4.2. are established during the development of task 4.1. Most important aspects can be classified as follows [1].

2.1.1. Sources of errors in wireless communication

This section describes QoS parameters that are typically used to estimate channel quality and considers sources of communication errors. Techniques that are used to maintain QoS are described in the next section.

Radio channel & communication channel

In its pure form, a *radio channel* is characterized by its fading and interference properties over time. However, the notion of a *communication channel* may be taken to include, apart from the radio channel proper, parts of network protocols involved, thus spanning medium access, low-level resend techniques, network layer, and even transport protocols such as UDP and TCP/IP. In this section we focus on the lower protocol layers, where as the higher layers above are covered to some extent in Section **Error! Reference source not found.**, where networked control performance over wireless link(s) is further explored.

Uncertainties on a communication channel sources, typically, from:

- **delay**,
- **jitter** (variance in delay),

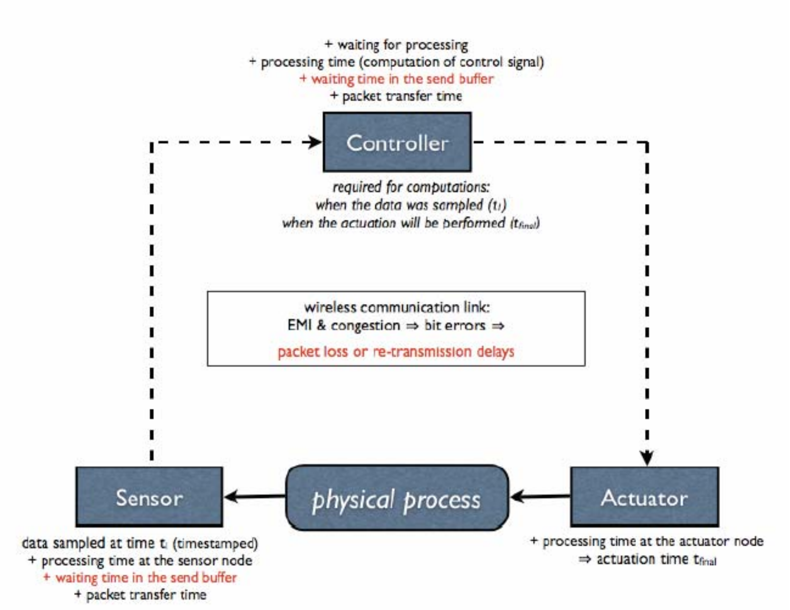

Figure 1. Sources of delay (and jitter) in the system

- bit error rate (and **packet losses** due to unrecoverable bit errors), and
- (resulting) available bandwidth.

Knowledge on such issues can be useful for controlling (tuning) the channel, e.g. adjusting the signal's transmission power, adapting/selecting modulation technique and error correcting code, and selecting a frequency band and/or a frequency hopping scheme. This information can also be used for tuning the protocols (admission/resend techniques), back-off strategies, etc. Finally, the parameters can be of direct use to the control application, e.g. by selecting, adapting, and tuning control strategies and communication schemes.

Radio channel errors due to fading and interference

Wireless communication, due to its use of shared unshielded medium, is inherently susceptible to channel fading and interference, which may lead to a communication failure.

1. *Channel fading* (within a normal range of operation) occurs due to a multi-path reception of the transmitted signal, and is location-dependent.
2. *Channel interference, on the other hand, is due to emission by external sources (such as unshielded electrical equipment), seen as noise in the frequency band(s) of the receiver.*

Communication channel errors due to congestion and node failure

1. *Congestion.* Congestion in wireless networks has been shown to lead to a significant decrease in throughput, which in turn leads to increased per-packet energy cost. Multi-path routing can be used to decrease congestion through load balancing, although this also means increased overhead.

2. *Intermediate node failure.* Intermediate node failure is an issue in wired as well as wireless networks. In both cases, the solution lies in having backup paths that can be utilized when a failure occurs. In wireless networks especially node disjoint paths are preferred over paths that are merely link disjoint, since nodes as well as links can fail in a wireless scenario.

2.1.2. Scheduling of wireless channels

The two most common methods for scheduling wireless channels are ALOHA-like protocols and TDMA-based networks.

Pure ALOHA is very inefficient, but improvements such as non-persistent CSMA (Carrier Sense Multiple Access) are common in practice. For instance, ZigBee in non-beacon mode uses CSMA/CD for communication. CSMA exists in a multitude of variants. A common focus for CSMA networks is average throughput and delay, which means that they are in general not suitable for hard real-time communication.

TDMA (Time Division Multiple Access) divides the channel into time-slots, allowing each node the use of a fixed number of slots. The schedule specifying the distribution of the time-slots can either be pre-computed or (more commonly in wireless networks) allocated at run-time via an admission control. Both GSM and Bluetooth use variants of TDMA. The main benefit of TDMA is predictability, each node can determine in advance when it needs to send or listen.

Other scheduling methods, such as FDMA (Frequency-Division Multiple Access), exist but are less widespread. Recent work on WiDom, in effect transplanting the collision-avoiding techniques of CAN into the wireless domain, shows great promises as a basis for a wireless real-time network since existing analysis methods can be used.

2.1.3. Recovery from failure at the network and protocol layers

In a wireless system, failures of communication are unavoidable, and a strategy is needed for dealing with them. Perhaps the most common way to deal with failures is through retransmission. Such functionality is implemented at multiple layers of the communication hierarchy. The physical layer can support retransmissions of packets on unrecoverable radio transmission errors, while at the higher layers packets can be resent due to congestion (congestion causes buffers to overflow and packets to be discarded). Common to resend mechanism is some form of handshaking, e.g. by requesting sent packets to be acknowledged on reception by the receiver.

Unfortunately, retransmissions have grave effects on real-time performance of a system, and usually dominate the PHY layer as source of jitter for packet delivery. Assessing delay as a parameter can be done, for example, by measuring round-trip times of package delivery or utilizing time-stamped packages if a common notion of time can be established. Jitter can be computed as the variance in delay of packages. In the case of in-order delivery protocols, the effect of resend mechanism can further influence the delay and jitter properties as a flow might be stalled though later packets have been successfully transmitted and received.

2.2. *Activity development*

We have decided to analyze through simulation communication aspects regarding: jitter effects, delay compensation, packet loss effects, clock synchronization / drift effects. The detailed results on these are contained in [2, 3].

The TrueTime environment was selected for simulation. TrueTime is a Matlab/Simulink-based simulator for real-time control systems. TrueTime facilitates co-simulation of controller task execution in real-time kernels, network transmissions, and continuous plant dynamics. [4]

2.2.1. *Results*

A basic (not necessarily realistic) scenario can be built by employing a control loop with at one sensor (S), one controller (C) and one actuator (A). The system cycles through a S-C-A execution loop with the period H.

Jitter. In an ***event driven*** controller case a jitter causes a delay equal to the jitter itself (Figure 2).
The delay introduced by the jitter is: $D = (t_4 - t_3) - (t_2 - t_1)$.

In the ***time driven*** case, instead, the problem could be more critical. In fact, if the actuator task is executed very close to the begin of the controller task, then, a small jitter could cause an extra delay in the actuation of a whole period H (see Figure 3). The control signal can not be actuated during the execution of the task of the 1st actuator, because it is not ready, but has to wait until the next one.

Clock drift. Consider the following scenario: the sensor sends the measurement through a network to a gateway or to an I/O board. The controller receives the data from this using a different protocol (typically Profibus or Fieldbus). After the computation, the control signal will be sent to the actuator using the same network used by the sensor. It is easy to imagine that, using two different network protocols, no synchronization between the controller and the rest of the system is guaranteed. Hence, if periodic tasks are used to execute the sensing, the actuation and the control calculation, and a drift of the clocks occurs, then an extra lag is introduced in the loop.

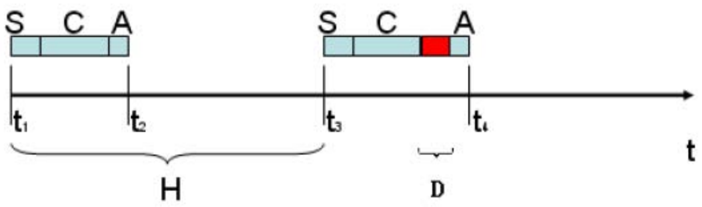

Figure 2. Jitter effect in event driven control.

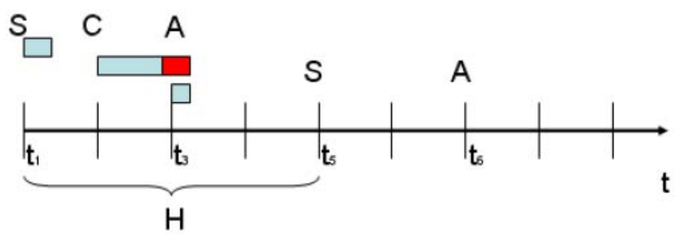

Figure 3. Jitter effect in time driven control.

If the clocks are not synchronized, the controller can execute when a new measure is not ready or with an extra delay. The control signal computed at time t_4 uses the measurement made at time $t1$ and it will be not actuated before the time

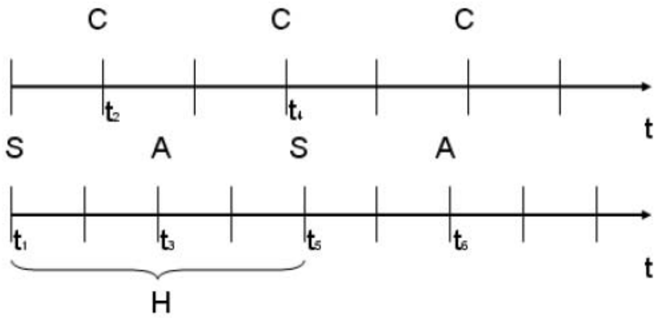

Figure 4. Delay caused by clock drift.

t_6. The total delay in this case will not be equal to standard delay $L = t_3 - t_1$, but to D: $D = t_6 - t_1 = H + L$.

Delay effect in different systems. To get an understanding of the problems caused by delays, it is interesting, first of all, to study how, different control loops react in presence of extra delay. Many plants in industrial applications are characterized by one of the following models: $G(s) = K / (T_s + 1)$, $G(s) = K / s$. Both these systems can easily be controlled using a PI controller of this type $C(s) = K_c \cdot (1 + 1 / T_I s)$

We analyze:

1. First order stable system affected by a delay

$$D_{sys}: G(s) = \frac{K}{Ts+1} e^{-sD_{sys}}$$

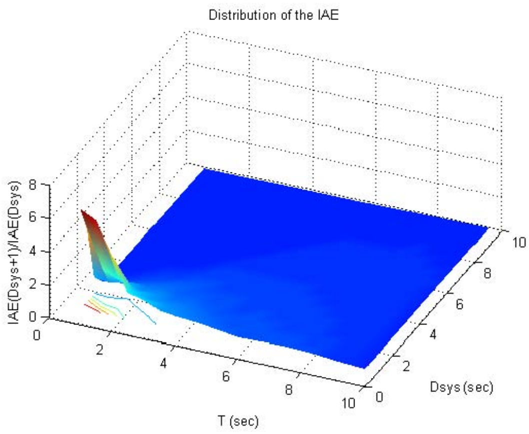

Figure 5. The IAE error changing the delay and the system time ct.

Figure 5 shows the ratio between the IAE (integral absolute error) using a controller tuned for D_{sys}, but applied to a system affected by a delay equal to $D_{sys} + 1$ and the IAE obtained applying the same controller to a system affected by a delay D_{sys}.

In the graph it is also taken into account the effects due to the shift of the time constant T. The extra delay gives performance degradation only in the corner case, when $T < 2$ and $D < 2$. It means that only in these lasts cases, it will be useful to adopt some delay compensation techniques.

2. Integrating (unstable) system affected by a delay D_{sys}:

$$G(s) = \frac{K}{s} e^{-sD_{sys}}$$

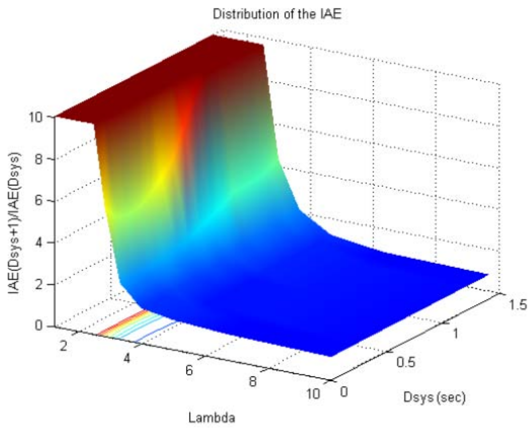

Figure 6. The IAE error changing the delay and the closed-loop time constant.

Figure 6 shows that the integrating system is more sensitive to the change of the parameters and suffers a degradation of its performance when $\lambda < 3$, for any value of the delay. Where λ is the desired time constant of the closed-loop system.

Packet loss. Packet loss can be caused by a number of different factors. These factors can be summarized in three points:
- channel interference
- channel fading
- collisions of packets transmitted by more nodes at the same time (only for networks using contention based MAC protocols, like CSMA or similar)

We have addressed different protocols, operating in the same band (ISM band 2.4 GHz) [5]:
- WLAN: non-deterministic (CSMA / CA protocol); least loss packages; power consumption: high.
- ZigBee: non-deterministic (CSMA / CA protocol); most loss packages; power consumption: low.

- WirelessHART: deterministic (TDMA protocol); average loss of packages (no contention); power consumption: low; speed: low

3. Problems and common results

It was necessary to identify problems affecting control aspects in a (wireless) networked environment. The most important ones were found to be jitter, clock drift, delays and packet losses. Appropriate scenarios are also required such that the effects are captured at their full extent.

Specialization of the problems was done as dictated by the specifics of ABB control devices (that is, having an impact on scheduling techniques). However, a generalization of the issues is not difficult.

4. Conclusion

The analysis of jitter, delays, clock drift and packet losses are the basis for finding solutions to such problems in communication over wireless connections. The results of MS4.2. contribute to the development of MS4.3. [5].

References

[1] SOCRADES deliverable D4.1.

[2] Mauro De Biasi. “Simulation of process control with Wireless Hart networks subject to packet losses”. M.Sc. thesis, 2008.

[3] Carlo Snickars. “Design of a WirelessHART Simulator for Studying Delay Compensation in Networked Control Systems”. M.Sc.thesis, 2008.

[4] TrueTime: “Simulation of Networked and Embedded Control Systems”. http://www.control.lth.se/truetime/

[5] SOCRADES milestone 4.3. “Simulation of wireless communication link for control purposes”.