Proceedings of the 17th World Congress
The International Federation of Automatic Control
Seoul, Korea, July 6-11, 2008

On the Implementation of one Process Control Application Type through a Network. Considering Three LANS: CAN, WiFi, ZigBee ⋆

Gérard Mouney* Guy Juanole* Christophe Calmettes**

* *LAAS-CNRS and Université de Toulouse*
(Université Paul Sabatier), 7 Avenue du colonel Roche
31077 TOULOUSE (FRANCE); mouney@laas.fr, juanole@laas.fr
** *Université de Toulouse (CUFR J-F Champollion)*
81000 ALBI (FRANCE); christophe.calmettes@univ-jfc.fr

Abstract: This paper wants to present the first reasoning in order to implement on a network a process control application type which is, in a first time, specified with a continuous model (transfer function in the Laplace domain). The network is a local area network and we only consider the MAC layer (frame scheduling) and the physical layer (serial frame transmission). By first reasoning, we mean that, we study the case of a network which is dedicated to the process control application type, and we want to link the stability and the reactivity that the application can get from the service provided by the network (link between the parameters of the open loop transfer function and the network characteristics (frame transfer, frame format, bit rate)). Three networks are considered: CAN, WiFi, ZigBee. This work is a basic work which wants to emphasize the necessary interplay between Automatic Control theory and Networks mechanisms.

1. INTRODUCTION

The Networked Control Systems (NCS) are nowadays emerging as a common architecture for embedded and autonomous systems. These systems implement distributed process control applications which require, for the transfer of data samples (data samples from a sensor to a controller, data samples from a controller to an actuator), a timeliness Quality of Service in order to guarantee performances (stability for example). The design of these systems requires an integration of techniques from computer science, communications and control, Zhang et al. [2001], Cervin [2003], Sename et al. [2003], Marti Colom [2002], Proceedings of the IEEE (special issue) [2007] . . .

The goal of this paper is precisely by considering the implementation of one process control application type through a dedicated network, to make the first connection which must be done between a network and a type of control process application. Such study is made by considering three local area networks (LANs) in order to compare them: a wired network, CAN (Bosch GmbH [1991], ISO 11898 [2003]), two wireless networks, IEEE 802.11 WiFi (Crow et al. [1997], Mangold et al. [2003]) and IEEE 802.15.4 ZigBee (Callaway et al. [2002], IEEE SA Standards Board [2003]).

This paper includes the following three sections. The second section presents the context of the study (the considered control system, the scheme of the implementation through a network, the considered LANs). The third section concerns the presentation of the constraints which are imposed by a network. The fourth section is dedicated to the determination of the transfer functions of the considered control system which can be implemented on the different networks and with what performances.

2. CONTEXT STUDY

2.1 The considered control system

The system is the classical regulation system the structure of which is represented on the figure 1. The output of the process to control is enslaved to a reference which represents the input of the system (the feedback is an unity feedback). The role of the controller is to provide performances in terms of stability, dynamic characteristics and accuracy in steady state. We will consider the frequency approach for modeling and analysis of our problem, models of the process and of the controller are described by transfer function based on a Laplace transform (Franklin et al. [2002]).

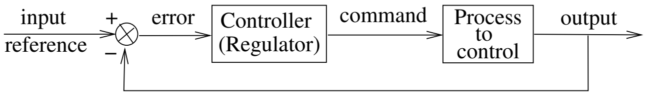

Fig. 1. Regulation system

Transfer functions The open-loop transfer function (product of the controller transfer function and the process to control transfer function) is

---

⋆ This work is supported in part by French ANR under grant ANR-ARA n° SSIA-NV-15.

$$G(s) = \frac{K}{s(1+\tau s)} \tag{1}$$

This type of transfer function is representative of a lot of processes which (due to the integration $\frac{1}{s}$) have no position error in closed-loop and for which dynamic characteristics and speed error are depending of the proportional correction (included in gain K of the open-loop).

The closed-loop transfer function $F(s)$ is a second order transfer function:

$$F(s) = \frac{G(s)}{1+G(s)} = \frac{\frac{K}{\tau}}{s^2 + \frac{1}{\tau}s + \frac{K}{\tau}} \tag{2}$$

$$F(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \tag{3}$$

with ω_n: natural pulsation and ζ: damping. We have the relations $\frac{K}{\tau} = \omega_n^2$ and $\frac{1}{\tau} = 2\zeta\omega_n$.

A fundamental criterion which is considered here is the stability one which is characterized by the phase margin

$$\phi_m = \pi + \arg\{G(j\omega)\} \tag{4}$$

$$\phi_m = \pi - \frac{\pi}{2} - \arctan(\omega\tau) \tag{5}$$

for $\omega = \omega_0$ such that

$$|G(j\omega)| = \frac{K}{\omega\sqrt{1+\omega^2\tau^2}} = 1 \tag{6}$$

Phase margin ϕ_m, damping ratio ζ and overshoot of the step response of the closed-loop transfer function are weakly connected: $\zeta \simeq \phi_m/100$ (up to the value of 60° for ϕ_m) and $D\% = e^{-\frac{\pi\zeta}{\sqrt{1-\zeta^2}}}$.
Note still the following performances: t_r (rise time) $\approx \frac{1.8}{\omega_n}$ and t_{resp} (response time at 5%) $\approx \frac{3}{\zeta\omega_n}$.

Specified performances We consider a regulation system which has a phase margin of 65° which implies $\arctan(\omega_0\tau) = 25°$ given by equation (5) (then $\omega_0\tau = 0.47$), and $K\tau = 0.5145$ (equation (6)). The closed-loop system has then a well damped time characteristic *i.e.* $\zeta = 0.7$ and $D\% = 5\%$.

Note that the *two relations*

$$\omega_0\tau = 0.47 \quad \text{and} \quad K\tau = 0.5145 \tag{7}$$

are representative of a set of open-loop transfer functions (different values of K and τ) which have a phase margin of 65° for a pulsation $\omega_0 = \frac{0.47}{\tau}$.

From these two relations, we can see that, higher is the value of ω_0 (*i.e.* lower is τ), higher also is the value of K. Note that higher is the value of ω_0, higher are the dynamics of the process control, and, higher is the value of K, better is the accuracy of the process control with respect to a speed step input.

2.2 Scheme of the implementation through a network

The regulation system implemented through a communication network is represented in the figure 2. The network operates both:

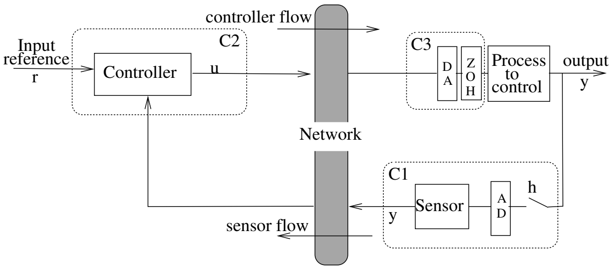

Fig. 2. Implementation through the network

- between the computer 1 (C1) associated to the numerical information provided by the AD conversion (this computer includes a task that we call the sensor task and which generates the sensor flow, noted sf) and the computer 2 (C2) where we have the reference and the controller (in C2 we have a task called controller task which generates the controller flow, noted cf),
- and between C2 and the computer 3 (C3) which provides numerical information to the DA conversion in front of the Zero Order Hold (ZOH).

The sensor flow goes from C1 to C2 and the controller flow goes from C2 to C3. The task which generates the sensor flow is time-triggered (the sampling is based on a clock) whereas the task which generates the controller flow is event triggered (the controller waits for the sensor sample receptions before computing and generating its flow).

2.3 The considered LANs

We present here the main elements of the basic functions of the networks that we consider: the MAC function which implements the scheduling of the data messages (coming from the application tasks) through the physical link (the data messages are encapsulated in frames); the physical layer function (electrical representation of the serial bits). A complete presentation of all networks is in Bosch GmbH [1991], ISO 11898 [2003], Crow et al. [1997], Mangold et al. [2003], Callaway et al. [2002] and IEEE SA Standards Board [2003].

The network CAN

– The frame scheduling is based on CSMA/CD scheme with a deterministic collision resolution based on priorities associated to the identifiers included in the data frames. The length in bits of a Data Frame (Navet [1999]) which results from the frame format is:

$$LDF = 47 + n + \lfloor \frac{34+n-1}{4} \rfloor$$

n being the payload field ($n \leq 64$ bits). In our study, as $n = 16$, we have $LDF = 75$.

– The physical layer does not add supplementary bits to the bits of a frame. We consider here a bit rate of 1 Mbits/s.

IEEE 802.11 Wireless Local Area Networks

– We consider for the frame scheduling the basic access mode (two way handshaking) of the Distributed Coordination Function (DCF) which is based on CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance) scheme:

use for the test of the free medium, of the time DIFS (DCF Inter Frame Space), SIFS (Short Inter-frame Space), and a random access backoff based on a Contention Window (CW); use of a frame ACK, the reception of which, allows to conclude that there was no collision; use of a post-backoff mechanism (after a successful transmission) in order to guarantee that there is always one random backoff time between two consecutive frame exchanges.
The length, in bits, of a Data Frame is:
$LDF = 272 + n$, n being the payload field ($n \leq 18496$).
In our study as $n = 16$, we have $LDF = 288$.
The length, in bits of an ACK frame is $LAF = 112$.
The initial backoff is chosen randomly, in term of slots times, in the interval $[0, CW_{\min} - 1]$ where $CW_{\min}$ is the initial width of CW (after each collision situation, CW is doubled until it reaches $CW_{\max}$).

– Concerning the physical layer, we consider the 802.11b protocol and the direct sequence spread spectrum (DSSS) modulation technique. This technique uses 2.4 GHz Industrial Scientific and Medical (ISM) frequency band. Several rates for the bits of the MAC frame are specified (here we only consider 1 Mbits/s and 11 Mbits/s). The physical layer adds 192 supplementary bits (for a preamble and a header) to the bits of the MAC frame. We note LPH the length in bits of this influence of the physical layer. These bits added by the physical layer are sent at 1 Mbits/s whatever the bit rate of the MAC frames. In the table 1, we give the parameters of the DSSS transmission.

Table 1. Parameters of the DSSS transmission.

slot time	20μs		
SIFS	10 μs	DIFS	50μs
$CW_{\min}$	31 (slot time)	$CW_{\max}$	1023 (slot time)
	620 μs		20460 μs

IEEE 802.15.4 (ZigBee)

– We consider the non beacon enabled mode which is based on unslotted CSMA/CA scheme: use of a random backoff time (during which, a station, which wants to transmit, has to wait before sensing the channel) which is based on the concept of backoff period (80 bits – duration 320μs) and Backoff Exponent (BE); the random backoff time is randomly generated in the range $[0, 2^{BE} - 1] \times$ backoff periods (the value of BE which is considered here is 3 (default value)); use of an ACK frame to control the collision occurrence (an ACK frame is sent by the receiver after a maximum Turn around Time (TT), the duration of which is 192μs (48 bits)).
The length in bits of a Data Frame is:
$LDF = 72 + n$, n being the payload field ($n \leq 944$).
In our study as $n = 16$, we have $LDF = 88$ bits.
The length, in bits, of an ACK Frame is: $LAF = 40$.
The timer SIFS is also used: $SIFS = 192\mu$s (48 bits).

– Concerning the physical layer, we consider here the 2.4 Ghz ISM band, which provides a transmission rate of 250 kbits/s. Note that the physical layer adds 48 supplementary bits to the bits of a MAC frame. We note still (as with IEEE 802.11) LPH the length in bits of this physical layer influence.

3. THE IMPORTANT CONSTRAINTS IMPOSED BY THE NETWORKS

The implementation of a process control through a network imposes that the sequential exchange of one frame of the flow sf and one frame of the flow cf must be realized during a sampling period. The duration of this exchange sets the limit (the smallest value) of the sampling period which can be implemented. The knowledge of this limit gives a information on the dynamics (*i.e.* the reactivity) of the process control which can be implemented. Smaller is this limit, higher will be the reactivity.
The implementation of the process control must also guarantee the property of stability. The stability (with respect to the stability of the continuous time model implemented without the network) must now take into account the delay induced in the loop by the sampling process and by the transfer of one frame of the flow sf and one frame of the flow cf. Higher is this delay, less good is the stability. We now precise these constraints for the three considered networks. Note that we neglect the propagation time (we can do it as we have local networks).

3.1 Evaluation of the limit of the sampling period

We represent on the figures 3, 4, 5, respectively for the networks CAN, IEEE 802.11 and IEEE 802.15.4, the progress of the exchanges and mechanisms in the MAC sub-layer and Physical layer, requested for the transmission of a data frame of the flows sf (going from the sensor (S) to the controller (C)), followed by the transmission of the flow cf (going from the controller (C) to the actuator (A)). On the figures 3, 4, 5 we have the lines marked S, C, A where are represented the frames sent respectively by S, C, A with also the necessary time mechanisms. Concerning the figures 4 and 5, the black part of the frame represents the bit added by the physical layer. From these time diagrams, we get the following inequality relations which express the limit of the value of the sampling period T_e (T_e must be higher than this limit).

- CAN: $T_e > 2\times$ Data Frame duration,
- IEEE 802.11: $T_e >$ Data Frame duration + SIFS + ACK Frame duration + DIFS +Data Frame duration + SIFS + ACK Frame duration + DIFS + post-backoff duration,
- IEEE 802.15.4 : $T_e >$ random backoff duration + Data Frame duration + TT + ACK Frame duration + SIFS + random backoff duration + Data Frame duration + TT + ACK Frame duration + SIFS.

The Data Frame duration (resp. ACK Frame duration) is obtained from the bit rate and from the length of the MAC and Physical frame, $LDF + LPH$(resp. $LAF + LPH$); in the case of WiFi the bits of the physical layer LPH are sent at 1 Mbits/s whatever the bit rate of the MAC frame. Concerning the post-backoff duration (WiFi), we take the value of the initial contention window *i.e.* 620μs (the initial window because we have no collisions as the network is dedicated to the application; this value is the maximum value which can be randomly chosen and it represents the worst case). Concerning the random backoff duration (ZigBee), we consider also the maximum value which can be chosen (2240μs) and then it is the worst case too.

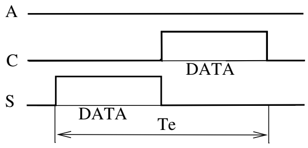

Fig. 3. The two successive flows in a sampling period (CAN)

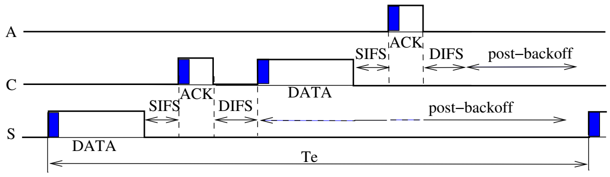

Fig. 4. The two successive flows in a sampling period (802.11)

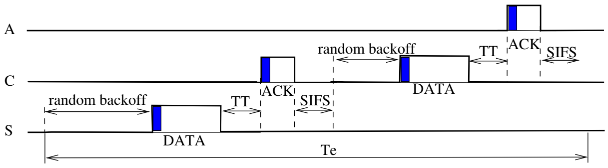

Fig. 5. The two successive flows in a sampling period (802.15.4)

Taking into account for the previous inequality relations and the bit rates of the three networks, we give on the table 2 the limit of the sampling period (noted $T_{e,l}$).

Table 2. Values of $T_{e,l}$ for the different networks

Bit rates	250 Kbits/s	1 Mbits/s	11 Mbits/s
CAN		150 μs	
WiFi		2308 μs	1580 μs
ZigBee	7040 μs		

3.2 Evaluation of the delays in the loop of the process control

The implementation through the network imposes the following delay τ_D:
$\tau_D = \tau_S$ (delay associated to the sensor flow)$+\tau_C$ (delay associated to the controller flow) + τ_Z (delay associated to the module ZOH).

Concerning τ_S, we have:

- CAN and IEEE 802.11: τ_S = Data Frame duration,
- IEEE 802.15.4: τ_S = random backoff time + Data Frame duration.

Concerning τ_C, we have:

- CAN: τ_C = Data Frame duration,
- IEEE 802.11: τ_C = SIFS + ACK Frame duration + DIFS + Data Frame duration,
- IEEE 802.15.4: τ_C = TT + ACK Frame duration + SIFS + random backoff time + Data Frame duration.

Concerning τ_Z: $\tau_Z = \frac{Te}{2}$ (approximation of the ZOH behavior) Franklin et al. [2002].
For our experiments we will take for the sampling period T_e a value greater of about 5% than the limit $T_{e,l}$. These values of T_e are 160 μs for CAN, 2400 μs and 1650 μs for the two bit rates used for IEEE 802.11 (1 and 11 Mbits/s) and 7400 μs for IEEE 802.15.4.

We give on the table 3 the numerical values of τ_S, τ_C, τ_Z and τ_D for the bit rates which are considered in the different networks.

Table 3. Network service delay for the three LANs

	τ_S (μs)	τ_C (μs)	τ_Z (μs)	τ_D (μs)
CAN 1 Mbit/s	75	75	80	230
WiFi 1 Mbit/s	480	844	1200	2524
WiFi 11 Mbit/s	218	480	825	1523
ZigBee 250 Kbit/s	1664	2400	3700	7764

4. WHAT PROCESS CONTROL APPLICATIONS AND WITH WHAT PERFORMANCES?

An implementation of a process control application must have the properties of stability (which depend on the phase margin) and reactivity (which depend on the rise time). We now study successively the requirement of stability and the requirement of reactivity.

4.1 Considering the requirement of stability

The delay, which has an effect on the loop, gives an information on the decrease of the phase margin (*i.e.* decrease of the damping ratio and increase of the overshoot) of the process control type. This delay, which is intrinsic to the network, cannot be avoided but in some application, we can admit performances which are lowered with respect to the standard performances (damping ratio) in the continuous system and then it can be interesting to determine families of transfer functions which can be implemented (*i.e.* where we can admit some damage in the performances with respect to the implementation without the network). All these analysis depend obviously on the network which is used.

The open-loop transfer function of the regulation application implemented through the network, considering the constant delay τ_D, is then:

$$G_1(s) = e^{-\tau_D s} G(s) = e^{-\tau_D s} \frac{K}{s(1+\tau s)}$$

Taking into account the delay τ_D the phase margin is now $65° - \omega_0 \tau_D \times \frac{180°}{\pi}$. The term $\omega_0 \tau_D \times \frac{180°}{\pi}$ represents the phase margin decrease (with respect to the transfer function reference $G(s)$).

If we impose us a maximum phase margin decrease, we get the maximum value for ω_0 ($\omega_{0\max}$). Then using the relations (7) given in the subsection 2.1, we obtain the range of the values of K and τ. For each network (*i.e.* considering its delay τ_D (table 3)) we report on the table 4 the values $\omega_{0\max}$, $\tau_{\min}$, and $K_{\max}$ for phase margin decreases of respectively 1°, 5°, 10°, 20°, 25°, 30°, 35° (associated

Table 4. Open-loop transfer function families for the three LANs

	Upper bound on the phase margin decrease						
	1°	5°	10°	20°	25°	30°	35°
CAN 1 Mbit/s							
$\omega_{0\max}$ [rad/s]	76	379	759	1518	1897	2277	2656
$\tau_{\min}$ [ms]	6.2	1.2	0.61	0.31	0.25	0.21	0.18
$K_{\max}$ [rad/s]	83	415	831	1661	2059	2470	2882
802.11 1 Mbit/s							
$\omega_{0\max}$ [rad/s]	6.9	34.6	69.1	138	173	207	242
$\tau_{\min}$ [ms]	68.0	13.6	6.8	3.4	2.7	2.3	1.9
$K_{\max}$ [rad/s]	7.57	37.8	75.7	151	188	225	263
802.11 11 Mbit/s							
$\omega_{0\max}$	11.5	57.3	114	229	286	344	401
$\tau_{\min}$ [ms]	41.0	8.2	4.1	2.1	1.6	1.4	1.2
$K_{\max}$ [rad/s]	12.5	62.7	125	250	311	373	435
802.15.4 250 Kbits/s							
$\omega_{0\max}$ [rad/s]	2.25	11.24	22.5	44.9	56.2	67.4	78.7
$\tau_{\min}$ [ms]	209	41.8	20.9	10.4	8.4	7.0	6.0
$K_{\max}$ [rad/s]	2.5	12.3	24.6	49.2	61.0	73.2	85.4

with overshoot of respectively $5\%, 8\%, 12\%, 22\%, 30\%, 35\%$ and 39%).

From the table 4 and more precisely the values of ω_0 and K, we can infer the following conclusions: for any damage which is admitted in the stability performances, CAN implements the applications which provide the best dynamics and the best accuracies (CAN has frames with the shortest durations). In the last position we have ZigBee because it has the longest durations for the frames (this is due to a great number of bits of a frame and also to the smallest bit rate) and it uses a waiting delay before to send a frame. WiFi is in between. Furthermore we can remark that the difference between WiFi-1 Mb/s and WiFi-11Mb/s is not too big (that is because they use the same contention window and also the physical part of the frame is long and based on a rate of 1Mb/s whatever the rate of the MAC part).

4.2 Considering in more the requirement of reactivity

From the limitations of the sampling period T_e, we have to specify the reactivity characteristics in terms of the rise time t_r that we can obtain. We have the relation $4 \leq \frac{t_r}{T_e} \leq 10$ which must be respected in order to obtain acceptable performances with respect to the continuous case Astrom and Wittenmark [1997].

As $t_r \simeq \frac{1.8}{\omega_n}$ and $\frac{K}{\tau} = \omega_n^2$, if we choose a value for t_r, we determine the natural pulsation ω_n (higher ω_n is, faster is the transient behavior of the output), and we get a new relation between K and τ. Then, considering the relations 7 ($\omega_0\tau = 0.47$ and $K\tau = 0.5145$), we determine now, for each network, the values of the parameters of one process control application (K, τ and then ζ and ω_n) and its performances when implemented on the network.

The choices of $t_r = 4T_e$ and $t_r = 10T_e$ represent in terms of reactivity requirements, respectively the strongest condition and a comfortable choice which procures a minor effect in relation with the continuous model. The table 5 illustrates (by the values of the gain K and ω_0) this comment and shows still the interest of CAN (in terms of reactivity) with respect to the two other networks.

Table 5. Parameters of one control application for each LAN

	CAN	WiFi 1 Mbits/s	WiFi 11 Mbits/s	ZigBee
T_e [ms]	0.16	2.4	1.65	7.4
$t_r = 4\,T_e$[ms]	0.64	9.6	6.6	29.6
τ [ms]	0.254	3.81	2.62	11.7
K	2009	134	195	43
ω_0 [rad/s]	1850	123	179	40
phase margin decrease [°]	24	18	16	18
$t_r = 10\,T_e$[ms]	1.6	24	16.5	74
τ [ms]	0.635	9.52	6.55	29.4
K	803	54	78	17
ω_0 [rad/s]	740	49	72	8
phase margin decrease [°]	10	7	6	7

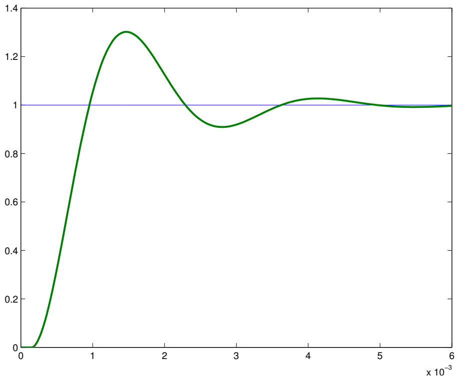

Fig. 6. Influence of the network delay (CAN network): $t_r \simeq 600\mu s$ and $D\% \simeq 30\%$

However we can still see from the table 5 (by the values of the phase margin and by looking, for example, on the part related to $t_r = 4T_e$) that CAN has the highest phase margin decrease, then a performance, from the stability point of view, less good than WiFi and Zigbee. We explain why: as CAN has a big value of ω_0 (with respect to the other networks) and though it has the smallest delay τ_D, the product $\omega_0\tau_D$ of CAN is still the highest. This means that more reactive a system is, more sensitive to the delay it is (*i.e.* more sensitive is the stability). The table 5 still shows that the performances of the two WiFi networks are not very different (see subsection *4.1*).

We represent, for the three networks when we choose $t_r = 4T_e$, the output of the process control implementation on the figures 6, 7 and 8. We can see both the performances of reactivity and stability.

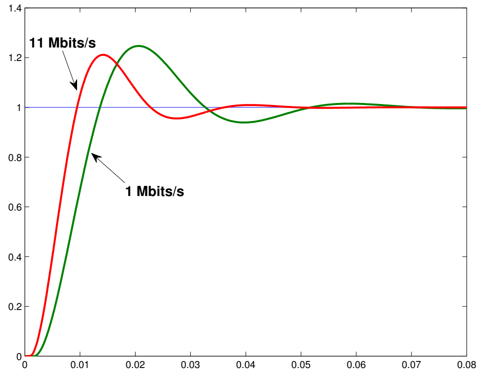

Fig. 7. Influence of the network delay – WiFi 1 Mbit/s ($t_r \simeq$ 9ms and $D\% \simeq 25\%$) and 11 Mbits/s ($t_r \simeq 6$ ms and $D\% \simeq 21\%$)

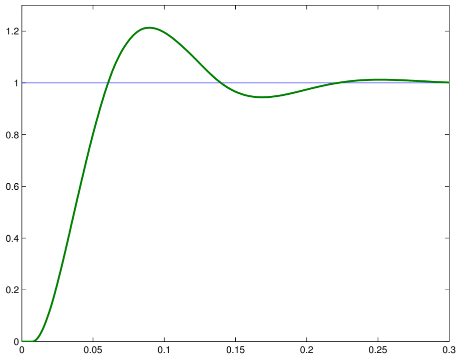

Fig. 8. Influence of the network delay (ZigBee: $t_r \simeq 35$ ms and $D\% \simeq 20\%$

5. CONCLUSION

This paper has presented on a simple example the link between the Automatic Control domain (parameters of the transfer function and their meaning, stability and reactivity) and the communication network domain (by limiting ourselves to the MAC layer and the physical layer we indicate the constraints of the sampling period and of the delay). This work represents in our opinion a basic knowledge which is necessary in the context of the great development of the Networked Control Systems. We have considered the networks CAN, WiFi and ZigBee in the case where they are dedicated to the implementation of one control process application type and we have shown their differences in terms of the allowed performances (stability and reactivity). Obviously these studies must be continued by considering shared networks (in order to see the influence of the environment *i.e.* the flows of other applications). We have already done such a study on the network CAN (Juanole et al. [2005], Juanole and Mouney [2007]). But we need now to study more deeply the wireless networks. In particular, we have on the one hand, to evaluate the limits of the CSMA/CA scheme as it is considered here and, on the other hand, to study the possibilities of the centralized scheme (PCF in WiFi; Beacon enable mode and Contention Free Period in ZigBee).

REFERENCES

Karl J. Astrom and Bjorn Wittenmark. *Computer-controlled systems – Theory and design.* International Edition – Prentice Hall, 1997.

E. Callaway, P. Gorday, L. Hester, Gutierrez J.A., Naeve M., Heile B., and V. Bahl. Home networking with IEEE 802.15.4: a developing standard for low-rate wireless personal area networks. *IEEE Communications Magazine*, 40:70–77, Aug 2002.

Anton Cervin. *Integrated Control and Real-Time Scheduling.* Department of Automatic Control, Lund Institute of Technology, 2003.

B.P. Crow, Widjaja I., Kim L.G., and Sakai P.T. IEEE 802.11 wireless local area networks. *IEEE Communications Magazine*, 35:116–126, sept 1997.

G. F. Franklin, J. D. Powell, and A. Emami-Naeini. *Feedback Control of Dynamic Systems.* Prentice Hall, 2002.

Guy Juanole and Gérard Mouney. Using an hybrid traffic scheduling in networked control systems. In *Proceedings European Control Conference 2007, Kos, Greece*, July 2007.

Guy Juanole, Gérard Mouney, Christophe Calmettes, and Marek Peca. Fundamental considerations for implementing control systems on a CAN network. In *Proc. FET2005, 6th IFAC International conference on Fielbus Systems and their Applications, Mexico, Mexique*, November 2005.

S. Mangold, Sunghyun Choi, G.R. Hiertz, O. Klein, and B. Walke. Analysis of IEEE 802.11e for qos support in wireless lans. *IEEE Wireless Communications*, 35:40–50, Dec 2003.

Pau Marti Colom. *Analysis and design of Real-Time Control Systems with Flexible Timing Constraints.* Universitat Politècnica de Catalunya, Departament d'Enginyera de sistemes, Automàtica i Informàtica Industrial, 2002.

Bosch GmbH. *CAN specification 2.0 (A).* www.semiconductors.bosch.de/pdf/can2spec.pdf, 1991.

IEEE SA Standards Board. *Part 15.4: wireless medium access control (MAC) and physical layer (PHY) specifications for low-rate wireless personal area networks (LR-WPANs).* IEEE Computer Society, 2003.

ISO 11898. *Road vehicles controller area network (CAN), Rev. 2003*, 2003.

Proceedings of the IEEE (special issue). *Technology of Networked Control Systems*, Jan 2007.

Nicolas Navet. *Evaluation de performances temporelles et optimisation de l'ordonnancement de tâches et messages.* Doctorat de l'Institut National Polytechnique de Lorraine, 1999.

Olivier Sename, Daniel Simon, and David Robert. Feedback scheduling for real-time control of systems with communication delays. In *Proc. IEEE International Conference on Emerging Technologies and Factory Automation, Lisbon*, September 2003.

W Zhang, M. S. Branicky, and S. M. Philipps. Stability of networked control systems. *IEEE Control Systems Magazine*, 21(1):84–99, February 2001.