Scalable Computing: Practice and Experience
Volume 10, Number 3, pp. 291–305. http://www.scpe.org
ISSN 1895-1767

WIRELESS SENSORS AND ACTUATORS NETWORKS: CHARACTERIZATION AND CASES STUDY FOR CONFINED SPACES HEALTHCARE AND CONTROL APPLICATIONS*

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Abstract. Nowadays developments in Wireless Sensor and Actuators Networks (WSAN) applications are determined by the fulfillment of constraints imposed by the application. For this reason, in this work a characterization of WSAN applications in health, environmental, agricultural and industrial sectors are presented. Two cases study are presented, in the first a system for detecting heart arrhythmias in non-critical patients during rehabilitation sessions in confined spaces is presented, as well as an architecture for the network and nodes in these applications is proposed; while the second case presents experimental and theoretical results of the effect produced by communication networks in a Networks Control System (NCS), specifically by the use of the Medium Access Control (MAC) algorithm implemented in IEEE 802.15.4.

Key words: real-time systems, wireless sensor and actuator networks, embedded systems, real-time monitoring and control

1. Introduction. Currently, there is a great interest in developing applications for monitoring, diagnosis and control in the medical, environmental, agricultural and industrial sectors, to improve social and environmental conditions of society, and increasing quality and productivity in industrial processes. The development of Wireless Sensor and Actuators Networks (WSAN) applications will contribute significantly to solve these problems, and facilitate the creation of new applications.

Some applications which can be developed using WSAN are:

- Medical Sector: economic and portable systems, to monitoring, recording and analyzing physiological variables, from which it is possible to indicate the status of a patient and detect the presence or risk of developing a disease. As well, developing systems for the detection and analysis of trends in the daily behavior of patients, contributing to timely detect the presence of a health problem, and providing an economically viable solution to patient care in societies where the old population is great.
- Environmental Sector: continuous systems monitoring of species in dangerous extinction, monitoring and detection of forest fire systems, etc.
- Agricultural sector: detection systems, microclimates monitoring and pest control, to reduce the use of agrochemicals and make an optimal control of pests; optimal use of water in irrigation systems, etc.
- Industry: economic systems and easy installation for monitoring, diagnosis and control of plants and industrial processes.

Some of the currently technological challenges in WSAN development are [1], [2], [3], [4], [5]:

- It is necessary to develop detailed models of the system components (hardware and software tasks, task scheduler, medium access control and routing protocols), in languages that allow correct specifications and the subsequent analysis of information processing, reachability, security, and minimum response time application, enabling analysis of end to end deadline in real time applications.
- Task scheduler and medium access control and routing protocols proposed in this area are mostly focused on the optimization of a single critical parameter of the application, which often affects considerably the performance of the others. Therefore it is necessary to create new cooperation forms between these levels of the application architecture, in order to take the most appropriate decisions for the system reconfiguration in relation to the application's quality of service (QoS). Additionally, current proposals consider QoS parameters directly linked to conventional parameters of the operation and communication between computers but not to particular application requirements, so do not allow achieving optimal performance in applications.
- It is necessary to develop analysis strategies for performance and stability of signal processing and control algorithms in this area, in order to guide the design towards a co-design methodology to develop the processing algorithm and the implementation of computer architecture, allowing to compensate the sampling period changes and jitter effects, and optimize other parameters such as power consumption.

*This work has been partially supported by the project D2ARS (CYTED)
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The previous paragraphs show how these developments are determined by the fulfillment of constraints imposed by the application, such as energy consumption, limited computing power, coverage of large areas and real time deadlines, etc. For these reasons, in this work a characterization of WSAN applications for health, environmental, agricultural and industrial sectors is presented, then two cases study are presented; in the first a system for detecting heart arrhythmias in non-critical patients during rehabilitation sessions in confined spaces is presented, as well as an architecture for the network and nodes in these applications is proposed; while the second case presents experimental and theoretical results of the effect produced by communication networks to the Networks Control Systems (NCS), specifically by the use of the Medium Access Control (MAC) algorithm implemented in IEEE 802.15.4.

The article is organized as follows, section 2 shows a classification and characterization of applications in health, environmental, agricultural and industrial sectors, section 3 presents the case analyzed, in section 4 a proposal for the nodes architecture is presented, the network architecture and its simulation results are presented in section 5, finally in section 6 the conclusions and future work are presented.

2. Classification of Applications. During the classification was detected that different application sectors share similar characteristics from a technological point of view, for this reason the classification and characterization was developed in five types of application rather by sectors [6], [7], [8], [9], [10], [11], [12], [13], [14].

- Type 1 applications are characterized by measuring sampling periods from one second to few hours, and no strict deadlines for the generation of the algorithms results. Additionally, these applications, developed in open spaces, must cover large areas and it is necessary to synchronize measurements in different nodes. Agricultural and environmental applications, designated to measure, record and to analyze environmental variables, primarily belong to this category. The energy sensors autonomy expects for each node varies from days to months; in some applications, in places without access to conventional energy sources, nodes are equipped with energy transducers like solar cells, which supply energy to the nodes batteries.
- Type 2 applications are developed in confined spaces and have greater computing capacity demanding than applications type 1, although there is not strict response time, either. Because they are in confined spaces and nodes are fixed, there are no restrictions on energy consumption since they can use conventional energy sources; however, the use of wireless networks is justified since it facilitates the installation, adaptability and portability of implementation, in addition to the lower costs of implementation. Such applications are fined mainly in industrial and agricultural sectors. The sampling periods range from one millisecond, for implementation of diagnostic algorithms, until a second for monitoring and supervision tasks. The diagnostic algorithms do not require continuous operation; therefore the samples can be stored before being processed.
- Type 3 applications. In this category, in addition to measuring and processing data requirements similar to those in applications type 2, grouped applications are required to process images and they are developed in open spaces, some of which are in the agricultural sector for the detection of pests, and environmental sector aimed at detecting fires. Some of the nodes are mobile and require few hours' energy autonomy, and then restrictions in terms of power consumption are large. At the same time it is also necessary for synchronization of the nodes. While, because of the algorithms used for image processing, the computing capacity, memory size and communication bandwidth requirements are greater than applications type 2.
- Type 4 applications. These applications differ from applications type 3 because they are developed in confined spaces, then the network's coverage is not demanding; energy sensors autonomy expected are also higher, becoming close to one week. Grouped healthcare applications to the detection of diseases are in this category with body area networks (BAN).
- Type 5 applications. In these applications a sample data should be sent every sampling period, and then sampling periods are limited by the minimum interframes time space of data communication protocols. For this category, a range of sampling periods between 50 milliseconds and a few seconds has been selected. In this category are the applications of industrial control process, which are developed in confined spaces, so the distance between nodes is not big, and there are not restrictions on energy consumption. The deadlines for generating actions are less than or equal to a sampling period, and it is necessary to guarantee end to end deadline. If these constraints are not fulfilled, the control system performance can be degraded significantly, even generating instability in the system, therefore, it is

important to synchronize the activities of the nodes that are integrated in the control loop. In addition, to improve the control system performance, it is important to limit the variability in the task jitter.

Table 2.1 summarizes the characteristics of the applications described. As a strategy to increase reliability in the presence of faults, and optimizing the applications QoS, this proposal also has considered the migration of components between the nodes, which will be reflected in the architecture of the network and nodes.

Table 2.1
Analysis of requirements for each application type.

Application	Computing capacity	Memory size	Communication bandwidth	Location	Node mobility	Real-Time	Networks's coverage	Energy autonomy	Syncro-nization
Type 1	Low performance	Low	$< 256kbps$	Yes	No	Only measurement	Open space 10 km	Months	Yes
Type 2	Low performance	Medium	$< 256kbps$	Yes	No	Only measurement	Confine space 100 m	There isn't restriction	Yes
Type 3	High performance	High	$1Mbps$	Yes	Yes	Only measurement	Open space 10 km	Hours	Yes
Type 4	High performance	Medium	$< 256kbps$	Yes	Yes	Only measurement	Confine space 1 km	Days	Yes
Type 5	Low performance	Low	$< 256kbps$	No	No	End-to-end and minimum jitter variability	Confine space 100 m	There isn't restriction	Yes

3. Arrhythmia Detection Algorithm. Actually cardiovascular problems have the highest mortality rate from natural causes in the world. The great interest in developing devices for clinical detection and continuous monitoring of such diseases, is based on these activities are limited by the information type and the moment that it is caught, so transitional abnormalities can not be always monitored. However, many of the symptoms associated with cardiovascular diseases are related to transient episodes rather than continuing abnormalities, such as transient surges in blood pressure, arrhythmias, and so on. These abnormalities can not be predicted therefore a controlled supervision analysis is discarded. The reliable and timely detection of these episodes can improve the quality of life of patients and reduce the therapies cost. For this reason in this work a WSAN architecture to address such problems is proposed, this application belongs to type 4 described in paragraph 2.

As an example, the detection of arrhythmias using data from electrocardiogram (ECG) measure, in patients who are moving during a rehabilitation activity in a confined space of 100m x 100m, as a rehabilitation center, was analyzed. The sampling period was selected from the ECG frequency spectrum, which, according to the American Heart Association, has 100Hz harmonics. The greatest amount of relevant information for monitoring and detection of arrhythmias is between 0.5Hz and 50Hz.

When analyzing the ECG frequency spectrum can be established that the relevant components of the signal (QRS complex and waves P and T) are up to 35Hz. Applying the sampling theorem a minimum sampling period of 14ms approximately is necessary, but for practical purposes a period of 3ms was selected.

For the detection and analysis of ECG the Pan and Tompkins algorithm was selected, [15]. The results of this algorithm are used by a maximums detection algorithm, which identifies the time when segments of the ECG wave were presented, figure 3.1. Subsequently the analysis of the separation time between two R waves, the duration of the QRS segment and the energy of the wave R is developed, which allows detecting the presence of arrhythmias [16].

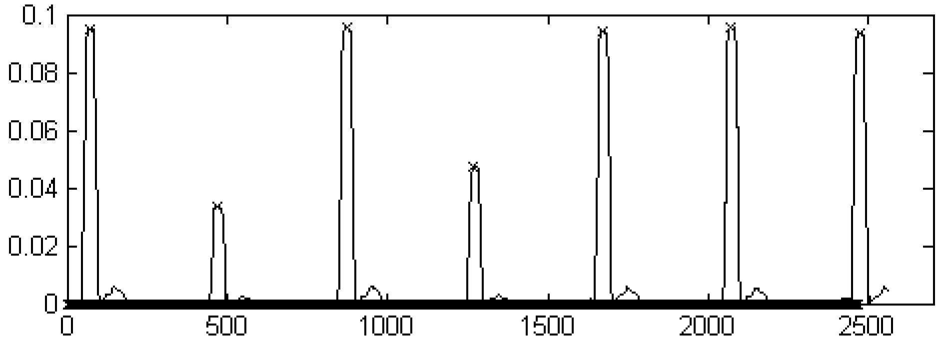

Fig. 3.1. *Results of maximums detection algorithm.*

4. Architecture Node. The proposed generic architecture for the network nodes in applications type 4 is presented in figure 4.1. Its characteristics are:

- The architecture enables the hardware and software components co-design. This feature will allow optimizing the development of distributed application components required for its implementation in hardware and software, getting a balance between cost, power consumption and processing time.
- There are fixed and mobile nodes. The latter are linked to the sub-network that guarantees them the best QoS (QoSsn) during its movement (less saturated sub-networks).
- Communication between the nodes and local coordinators is done through wireless networks.
- Use an EDF scheduler and dynamic scaling voltage and frequency techniques of the processor to optimize the power consumption [17]. This allows fulfilling the application deadlines, which is supported on statics utilization rate tables for each operating frequency, and periods of execution for each task.
- Update its QoS indexes (QoSn); using these indexes and its neighboring ones it is possible to request to another node in its sub-network the migration, creation or destruction of components (some of which are clones of others).

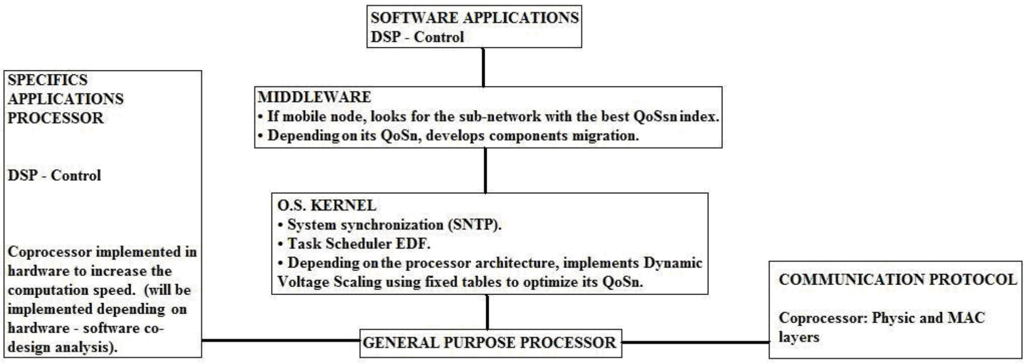

Fig. 4.1. *Nodes architecture.*

To select a set of architectures for an adequate performance of these applications, the performance of the arrhythmia detection algorithm, presented in section 3, was analyzed on four types of processors currently used to implement nodes in sensor networks: ARM7TDMI, MSP430, PIC18 and MC9S08GB60. For the analysis, the same operation velocity for each processor was used, 8MIPS. The time necessary to develop the Pan and Tompkins algorithm is presented in Table 4.1, which was estimated considering the sum of the values of individual functions (derivative, quadratic function and integrator window) in each architecture.

Table 4.1
Computing time to develop the Pan and Tompkins algorithm.

Processor	Derivative	Quadratic function	Integrator window	Total computing time	Period	Percentage of utilization (U)
LPC2124-ARM	70.2μs	142μs	280.5μs	492.7μs	3000μs	16.4%
MSP430F1611	191.9μs	162.5μs	697.8μs	1052.2μs	3000μs	35%
PIC18F458	406.2μs	209μs	1083.7μs	1698.9μs	3000μs	56.6%
MC9S08GB60	497.2μs	332μs	707.35μs	1536.55μs	3000μs	51.3%

The results show that the ARM architecture requires a lower percentage of utilization, while the PIC architecture needs the highest utilization percentage.

It also was related consumed power by each architecture in active mode (P_A) with the respective percentage of utilization during the implementation of the algorithm, table 4.2. It can be seen as the ARM7 architecture has a closer performance to the architecture MC9S08GB60; then these two architectures are appropriate for the implementation of the case proposed. The MSP430 architecture presented the best indicator.

Table 4.2
*Indicator PA*U.*

	Utilization percentage (U)	Active Power (P_A) [mW]	$P_A * U$
LPC2124-ARM	16.4%	180	29.52
MSP430F1611	35%	19.2	6.72
PIC18F458	56.6%	220	124.52
MC9S08GB60	51.3%	51.6	26.47

5. Network Architecture for Confined Spaces Healthcare Applications. In figure 5.1, a generic architecture for network applications type 4, which integrates different types of nodes, is proposed. The approach of a cooperation plan between architecture levels of the application, in order to take the most appropriate decisions for the reconfiguration of the system in relation to the application QoS, can be appreciated. General goals of the architecture are:

- Minimize latencies.
- Optimize power consumption.

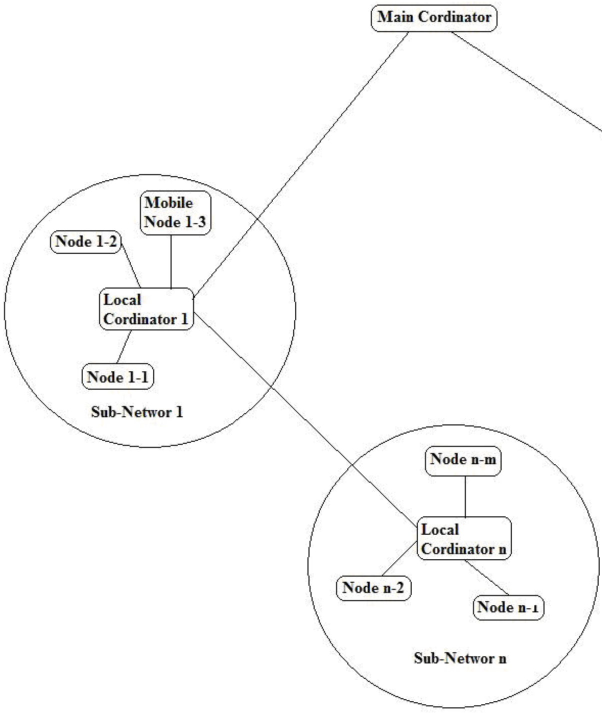

Fig. 5.1. *Network architecture.*

The Main Coordinator is responsible for coordinating the complete application. It will have a fixed location, and communication with local coordinators will be supported through wireless or wired links. It develops the following functions:

- Send synchronization signals to the local coordinators of the sub-networks.

Local Coordinator controls the activity inside the sub-network and develops some information processing activities, whose architecture is presented in figure 5.2 and its features are:

- It has a fixed location.
- Sends synchronization signals to nodes in its sub-network.
- Develops routing packets between sub-networks using multihop techniques.
- Distributes QoS indexes of nodes which belong to its sub-network (QoSn).
- Calculates its sub-network QoS index (QoSsn= f(quantity of information to be transmitted)), and distributes this value and its neighboring sub-networks indexes (those reached in a single communication hop) between nodes in its sub-network. Depending on which:
  - Accepts linking new nodes to sub-network.
  - Updates best routes in the routing tables of data (which will be function of hops and the utilization percentage—information transmitting—of each router node).

As a first approximation to the proposed architecture, we examined the performance of the case analyzed on the IEEE 802.15.4 protocol. Considerations for the proposed solution to the case are:

- Transmission of the analysis results, from nodes located on each patient to a main node, every 3 s. The data frame consists of 2 Bytes, which contain patient codes and the type of arrhythmia detected.
- After each sending the sender node waits for an acknowledgement (ACK) from next node in the routing path. If there isn't an answer before 100ms the node sends again the information. If after 25 attempts

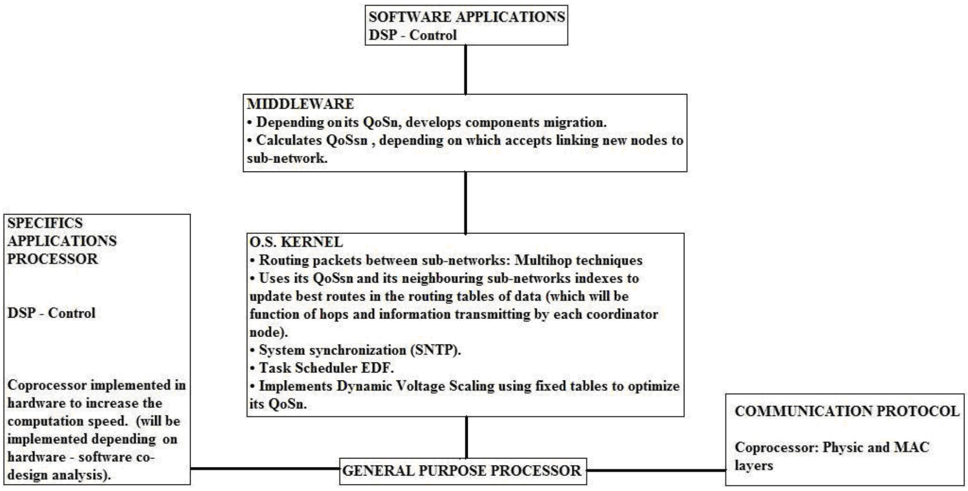

Fig. 5.2. *Sub-network coordinator architecture.*

there is no answer this node changes to a mistake state.

- The communication protocol selected is IEEE 802.15.4. The node distribution is shown in figure 5.3, which allows covering all possible locations of patients considering the specifications of the devices selected to implement the physical layer, CC2420, whose characteristics are:
  - Coverage radio of 30m, and 100m without obstacles.
  - Frequency range of 2.4–2.4835 GHz.
  - Supports data transfer rates of 250 kbps.

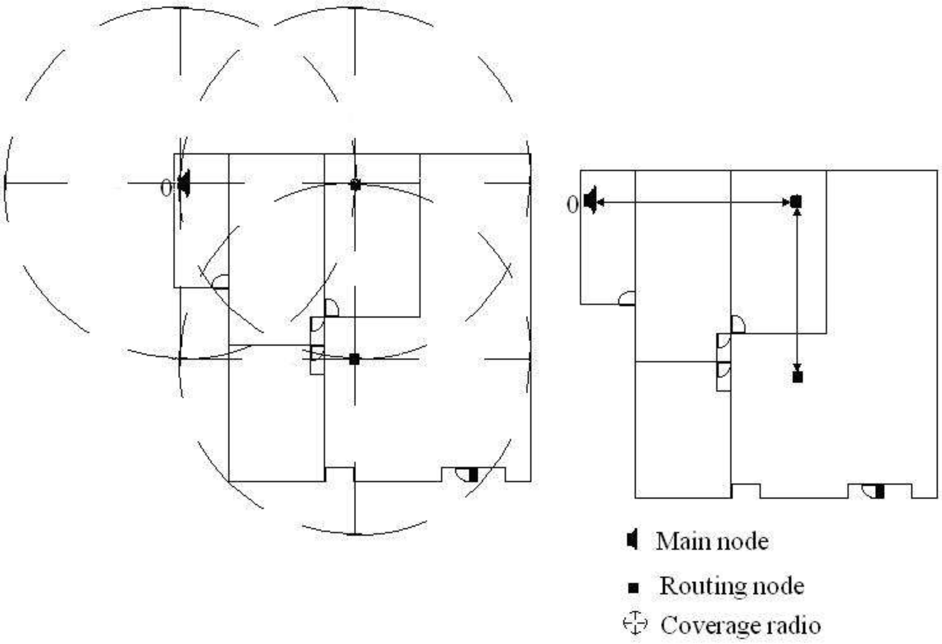

Fig. 5.3. *Distribution nodes for case and their coverage.*

In the case a network as presented in figure 5.4 was proposed. It consists of 3 fixed nodes which have no restrictions on power consumption, will receive reports from five patients and route the messages to the main node. The fixed devices have fixed identifiers 0, 1 and 2; the main node has the 0 identifier, and devices on every patient have identifiers from 3 to 7. The routing is developed through 1, 2 and 0 nodes, 0 is the network coordinator, each of these nodes forming a sub-network together with patients, figure 5.4. The mobile nodes leave and enter the sub-networks continuously changing the configuration and network structures.

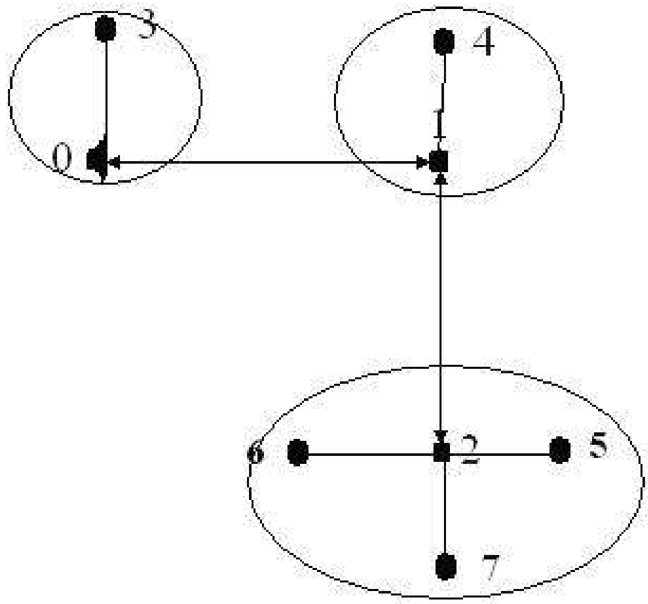

Fig. 5.4. *Network structure for case.*

The simulation was developed in the TOSSIM tool, and the TelosB platform was selected, including the CC2420 transceiver. Because the characteristics given of the case, with fixed nodes to implement the routing protocols, a routing fixed table algorithm was implemented, it is presented in table 5.1.

Table 5.1
Routing Table.

Source node	Destination node
2	1
1	0
0	

In the simulation was considered the most critical case, where all mobiles nodes are connected all time to the farthest sub-network from the main node.

Times obtained in sending 2 Bytes from all patients to the main node (node 0), are presented in table 5.2. The $data_1$ indicate that transmitting the message from a mobile node to the main node was over; the $data_2$ indicate that the corresponding node has not received the ACK. Times obtained demonstrated that it is possible to fulfill the constraint of 3s, for the transmission of patient status from a mobile node to the main node, which was imposed by the case analyzed.

6. Temporal Behavior of Networked Control Systems Over IEEE 802.15.4. Consequence to the increasing complexity of control systems most of activities have been distributed over different nodes, which control loops are closed through a communication network, these systems are called Networked Control Systems (NCS). The implementation of NCS also reduces the impact of failures in a system component and facilitates the diagnosis, maintenance and traceability processes.

Since the mobility of the elements that constitute the nodes in industrial processes is very low, the applications in this sector do not demand the strict use of wireless networks, for this reason in most cases wired networks are used, this is also consequence of reliability of wired networks and the ability to support transmission periods smaller than wireless networks. However, the development of new applications on wireless sensors and actuators networks (WSAN) will allow integrating wired and wireless networks to increase the applications flexibility and reliability, at the same time its impact on implementation reduction cost is significant.

This section presents the performance analysis of a NCS, using the MAC algorithm CSMA/CA implemented in IEEE 802.15.4 protocol. The generic diagram of the NCS considered in this work is presented in figure 6.1, which regulates the output signal in a second order system implemented with operational amplifiers. It has three types of nodes:

TABLE 5.2
Time in sending 2 Bytes from all patients to the main node.

Source node	Receiver node	Time (s)		Source node	Receiver node	Time (s)
6	2	78.309		0	$1(ack)_1$ - 5 ends	.613
4	2	.320		7	2 Rtx_2	.684
7	2	.333		3	2 Rtx_2	.684
2	6(ack)	.344		2	1 Rtx moving 4_2	.684
5	2 Rtx_2	.355		1	2 (ack)	.701
2	1 (moving frame from 6)	.380		7	2 Rtx_2	.714
3	2 Rtx_2	.380		1	0 (moving frame from 4)	.740
1	2(ack)	.397		2	7 (ack)	.746
1	0 (moving frame from 6)	.421		0	1 $(ack)_1$ - 4 ends	.764
5	2 Rtx_2	.421		2	1 (moving frame from 7)	.780
3	2 Rtx_2	.463		3	2 Rtx_2	.780
2	1 (moving frame from 5)	.486		1	2 (ack)	.792
7	2 Rtx_2	.486		3	2 Rtx_2	.807
2	5(ack)	.488		2	3 $(ack)_2$	.825
0	$1(ack)_1$ - 6 ends	.488		2	1 (moving frame from 3)	.860
1	2(ack)	.500		2	1 Rtx moving 3_2	.877
4	2 Rtx_2	.513		1	0 (moving frame from 7)	.877
3	2 Rtx_2	.524		0	1 $(ack)_1$ - 7 ends	.913
7	2 Rtx_2	.535		2	1 Rtx moving 3_2	.929
2	4(ack)	.547		1	2 (ack)	.949
2	1 (moving frame from 4)	.581		1	0 (moving frame from 3)	.979
1	0 (moving frame from 5)	.589		0	1 $(ack)_1$ - 3 ends	79.013

- Sensor, performs the measurement of the controlled signal and sends a frame with this information by the network.
- Controller-Actuator, receives a measure of the signal controlled, calculates the control action and acts over the manipulated signal in the system.
- Noise generator, generates network traffic.

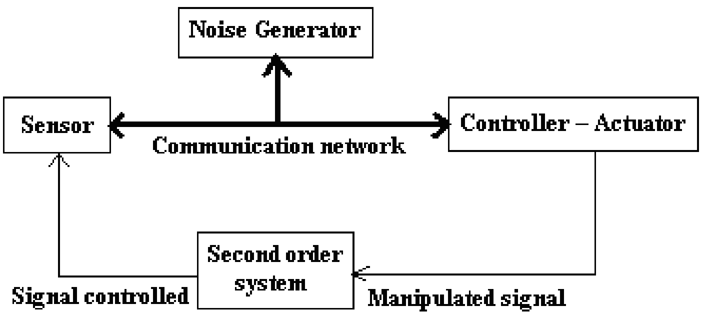

FIG. 6.1. *Generic diagram of the NCS considered.*

At the moment of design a high performance NCS is not always obtained similarity between experimental results and simulation, this is because imprecise models for analyzing and designing these systems are used, and for to make use of inadequate validation methods and platforms that not support the models used. There are several authors who have analyzed the performance and stability in NCS assuming network protocols with constant and variable delays, this shall also have made proposals to modified the control algorithms in order to respond to these effects, [18], [19], [20], [21]. An analysis of the performance of wired networks for control process is presented in [22]. In [23] the analysis of use 802.11b and Bluetooth networks in control systems is presented.

The transmission period in NCS is defined as the time between two consecutive transmissions, and is measured on- line for each communication segment. In NCS the transmission time between sensor and controller nodes can be periodic or aperiodic, being affected by delays depending on the Medium Access Control (MAC) protocol of the communication network, communication errors, Jitters and tasks scheduler.

The difficulty in the analysis and design of NCS is consequence of delays in the feedback control loops, because the behaviour of each component can affect the performance of control algorithms. Depending on the magnitude and variability of delays the performance of control systems can be degrade and can even present stability problems.

In the case study considered in this work, figure 6.1, the controller and actuator are in the same node (Controller-Actuator), so a single delay in the feedback control loop is considered, τ, which includes the processing time in the Sensor node, the network transmission time and the processing time in the Controller-Actuator node. The system was modelled by:

$$G_{p(s)} = \frac{20.3759}{s^2 + 3.497s + 21.73} \tag{6.1}$$

The regulator algorithm was designed as a PID algorithm using the Ziegler-Nichols closed-loop method, whose transfer function is:

$$G_{c(s)} = \frac{0.8909s^2 + 3.2322s + 20.201}{s} \tag{6.2}$$

It's representation in discrete time is: $u_k = u_{k-1} + q_0 e_k + q_1 e_{k-1} + q_2 e_{k-2}$; $q_0 = kp + \frac{kd}{T_m}$; $q1 = -kp - \frac{2kd}{T_m} + kiT_m$; $q2 = \frac{kd}{T_m}$

As a first approximation to analyzing the case study τ was considered constant. Using a Pade second order polynomial to model the delay, an approximation to the stability region for the feedback control system was found [24], [25], figure 6.2. It gives information of sampling period (T_m) and τ values for the system stability. This information can be used to choose the periods and deadlines to implement the control system.

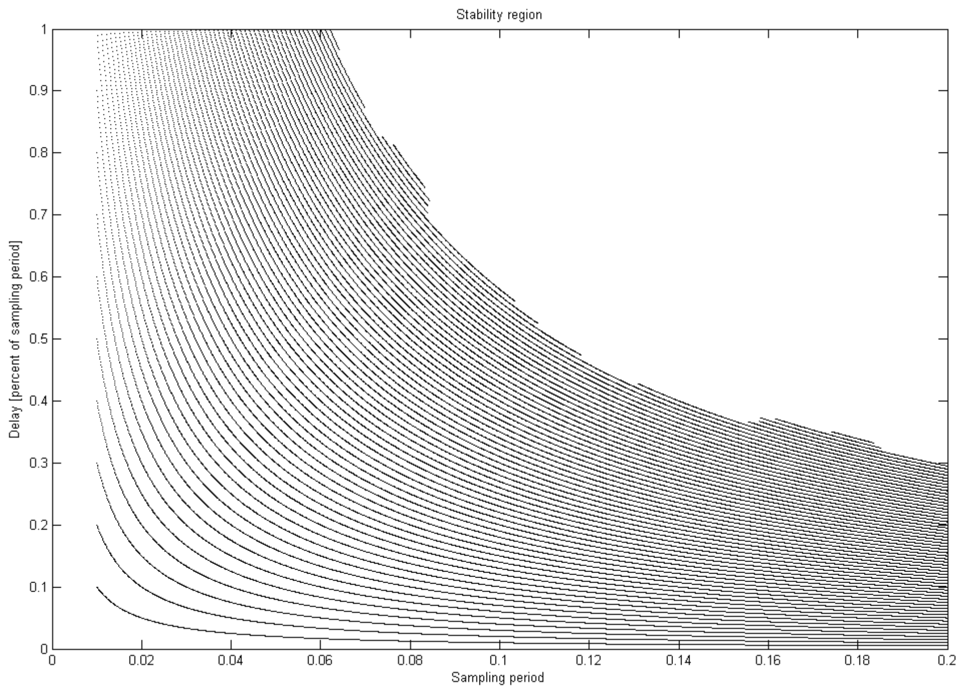

Fig. 6.2. *Stability region.*

Figures 6.3, 6.4 presents the control system output for different values of T_m and τ. and . It is possible to see how increasing the sampling period the system is more sensitive to delays, and although the system is stable to the considered values there is a large degradation in the performance of the control system, which could not ensure the desired performance in some cases.

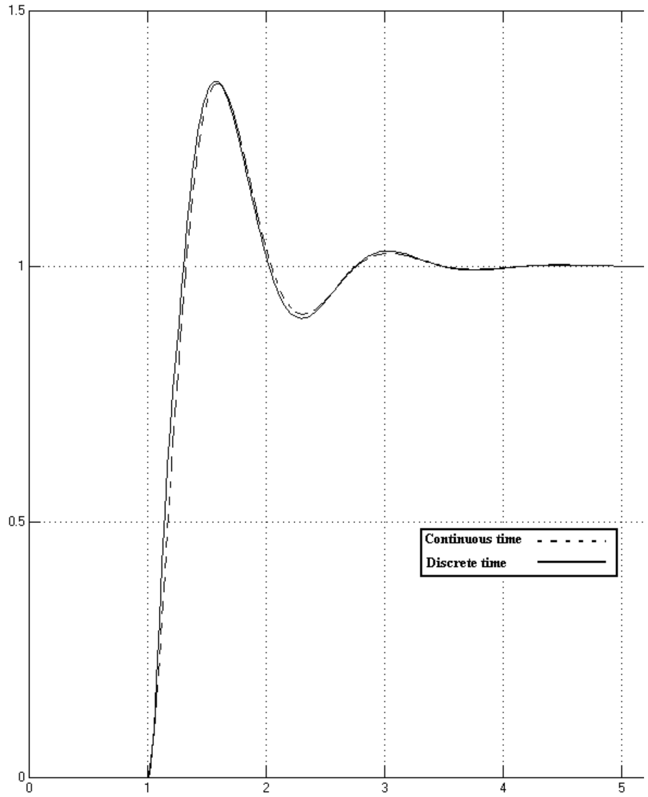

FIG. 6.3. *Control system output in continuous and discrete time for* $T_m = 23ms$, $\tau = T_m$.

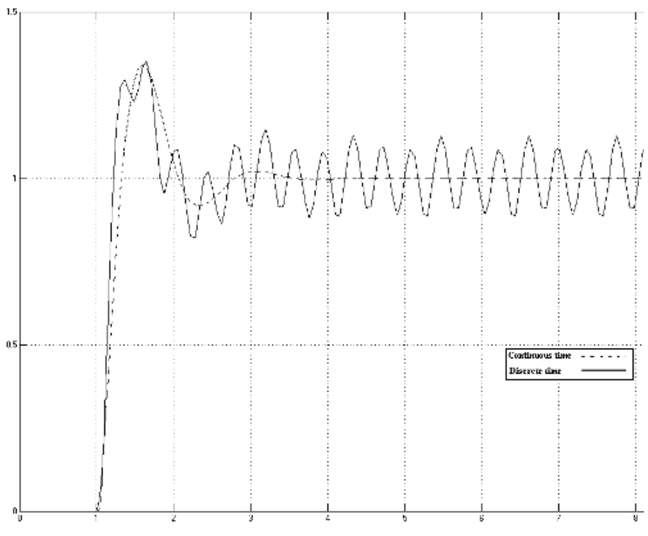

FIG. 6.4. *Control system output in continuous and discrete time for* $T_m = 57ms$, $\tau = 0.5T_m$.

To analyze the NCS considered the Truetime simulator was used [26]. Only the effect of MAC protocol was considered and the time processing in the nodes was ignored. The simulation parameters were:

- Sampling periods for the controlled signal: 50ms.
- Synchronization by events between nodes Sensor and Controller-Actuator.
- Data rate: 250 kbps.
- Frame size of 82 bits. Enough to send the measure of a variable.
- Two Noise generator nodes were implemented, with periods of 700 μ s and 900 μ s, and frame size of 82 bits each one.

The simulation results are presented in figure 6.5. It is possible to see how the time for sending information by CSMA/CA is variable and unbounded. Delays in the feedback control loop do not affect significantly the performance of the system, figure 6.6.

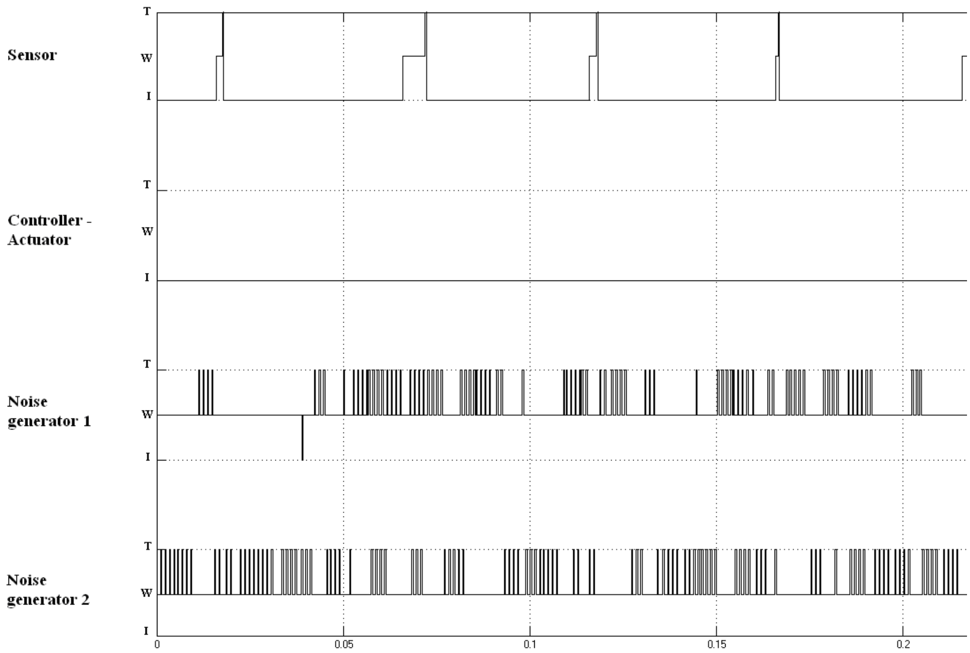

FIG. 6.5. *Network schedule. Levels T, W, and I represents Transmitting, Waiting and Idle states in every node.*

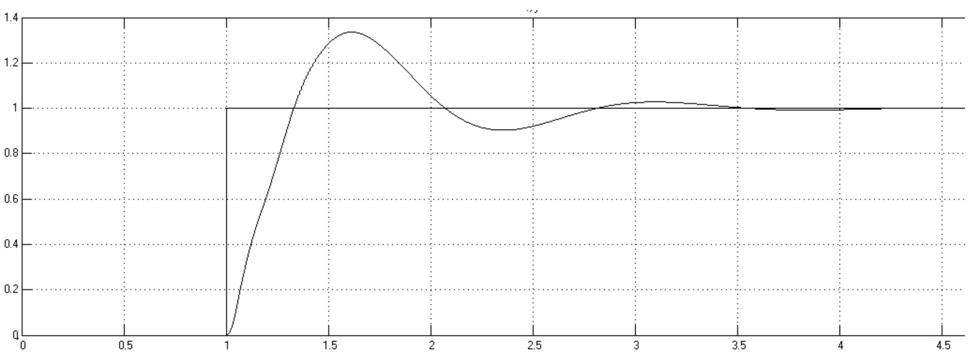

FIG. 6.6. *System response.*

The network was saturated by using transmission periods smaller than previous cases in the Noise generator nodes, figure 6.7, which was noted than despite loss of information transmitted by the Sensor node as a consequence of collisions with noise frames, the Sensor can retransmit several times before next transmission period, then the Controller-Actuator node get the measure before a critical τ (according to the stability region) and the system is stable, but the performance of control systems is degraded, figure 6.8.

7. Implementation of NCS. The implementation of the NCS was developed on IEEE 802.15.4 mode CSMA/CA. To develop the Sensor and Controller-Actuator nodes boards with the CC2430 processor were used, also the abstraction levels HAL and OSAL from Texas Instruments were used to access the hardware and to implement tasks. Two Noise generator nodes were implemented by MACdongle devices. The configuration was as follows:

- The Sensor node sends a frame every 60 ms. This period was selected because it was experimentally observed that lower values for the period was not stable as a consequence of computing in the node.
- In the Controller-Actuator node an event is generated for every message received from the Sensor node. During its attention the control output is calculated and acts on the system. Experimentally an interval

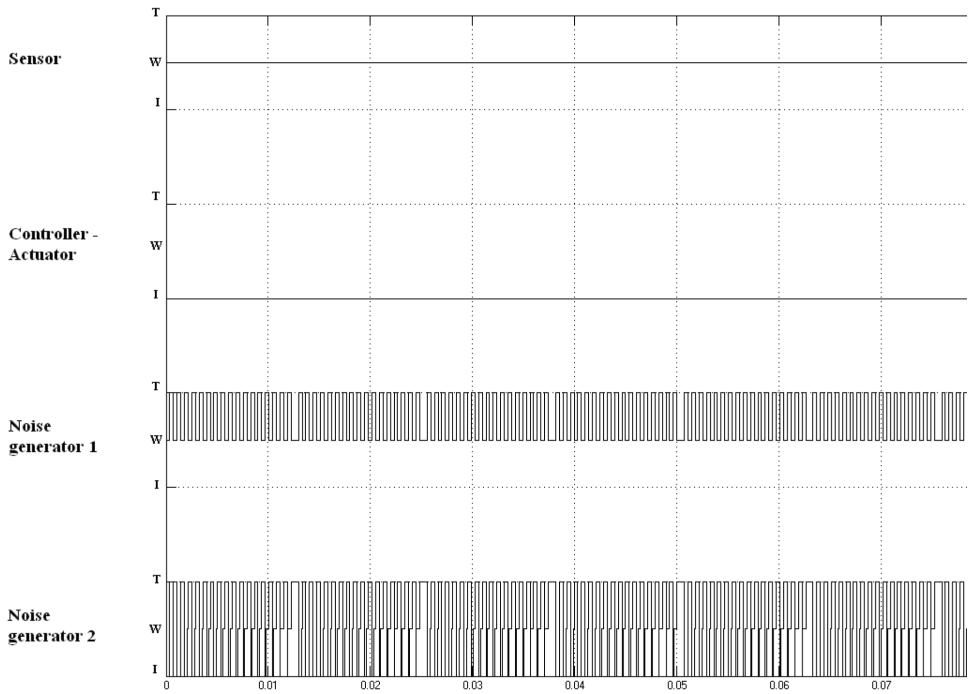

Fig. 6.7. *Network schedule with network saturated. Levels T, W, and I represents Transmitting, Waiting and Idle states in every node.*

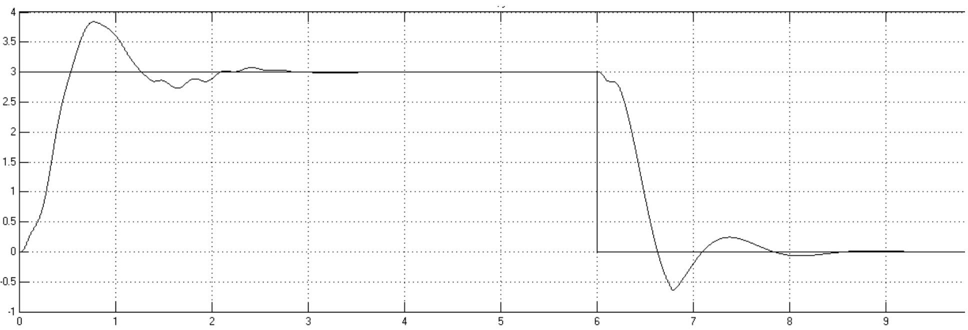

Fig. 6.8. *System response for network saturated.*

time between 12 ms and 16 ms was obtained from the time start measurement in the Sensor node until Controller-Actuator node acts on the system.
- The Noise generators nodes send a frame every 30ms.
- The size of the frame is 256 bits and the data rate is 250 kbs. Then the time of sending a frame is 1.024 ms.
- The nodes were distributed in an area of 1 m^2.

The Truetime simulations and experimental results are shown in figures 7.1, 7.2, 7.3 and 7.4.

As a result to the delay generated to frames from Sensor node, as a consequence of collisions in the network with frames sending from Noise generators nodes, in figure 7b can be seen than the transmission period is variable and it is not bounded. Moreover, the feedback delay is small compared to the dynamics of the system, and therefore the system is not significantly disturbed.

Experimental results are close to those gotten by simulation in Truetime.

8. Conclusions. From the study it can be concluded that developments on specific technologies and applications in this area are still emerging, and developing them will enable the growing of great social impact new applications.

About the system for detecting heart arrhythmias:

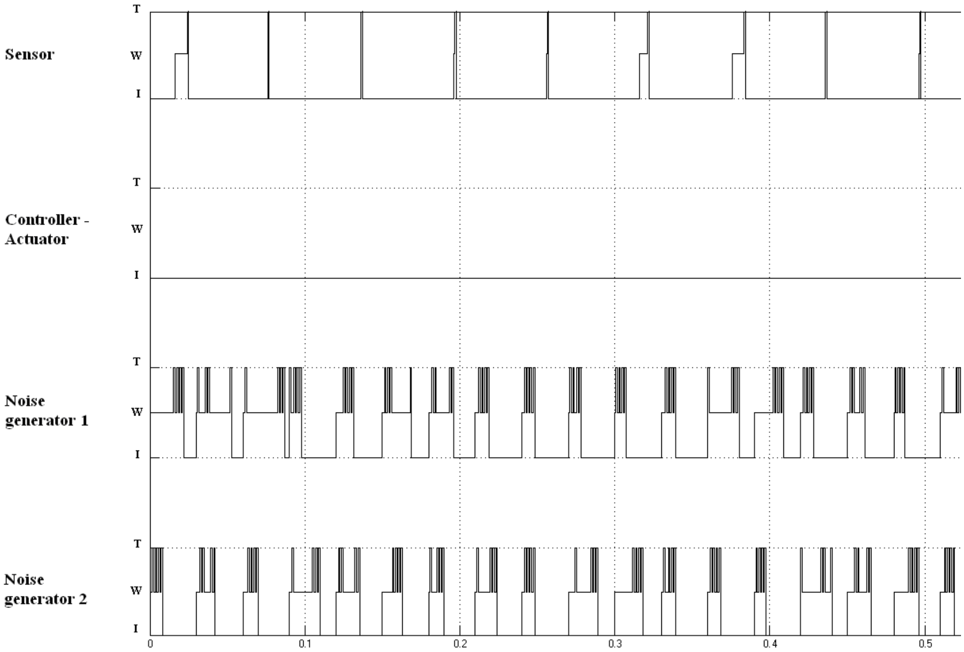

FIG. 7.1. *Simulation results of Network schedule.*

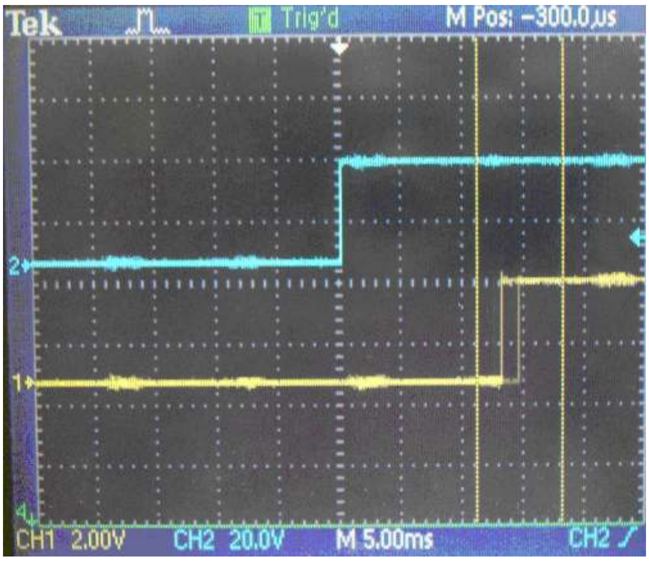

FIG. 7.2. *Experimental results of message time delay.*

- The proposed architecture considers the constraints of application field, allowing to find optimal solutions to the challenges in network and nodes designing, and will facilitate the development and validation of applications. It makes possible too the cooperation between levels of the network architecture to choose between different operations modes depending on QoS indexes.
- It is noted as the routing algorithm based on fixed tables supported by IEEE 802.15.4, fulfils the time requirements of these applications. Also as MSP430 architecture presents a good performance for the implementation of the case considered.

The impact of delays in the feedback loop of NCS was analyzed with formal methods, simulation and experimental results, which concludes:

- The technology considered in this paper can be used in control applications, where transmission times are not very demanding, particularly we propose use in cases with transmission periods upper then 100 ms.

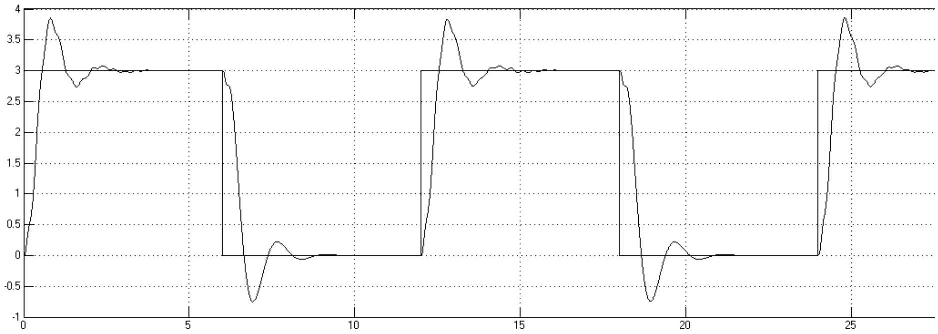

Fig. 7.3. *Control system output implemented on 802.15.4 mode CSMA/CA with two noise generators operating every 30 ms.*

Fig. 7.4. *Experimental values of control system output.*

- For big sampling periods the system is more sensitive to delays in the feedback loop, so it is important to maintain delays bounded.
- To control systems with transmission period less than 100 ms is recommended the use of wired networks, which is possible to get transmission periods smaller and stable than IEEE 802.15.4 mode CSMA / CA.
- There is a great similarity between the results using formal methods, simulation and physical implementation of the system. Then is possible to conclude than the analysis methods (stability region) used and simulation environments as Truetime, allow a fast analysis and reliable of such applications, which facilitates the design process of real NCS.

The future work proposed is the performance analysis of different task schedulers and routing protocols on the presented architecture, and a cooperation strategy between them to minimize power consumption.

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Edited by: Janusz Zalewski
Received: September 30, 2009
Accepted: October 19, 2009