Case study of wireless networked control system: CONECS and COWNECS platform

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Abstract – Many techniques for the enhancement of the quality of control have been studied in the networked control systems based on differentiated services, synchronization or dynamic aproaches. By controlling the resources of the network, a compromise between the offered quality of service and the required quality of control can be established. In the case of a multi hop control loop, using IEEE 802.15.4 for instance, the quality of control can be affected by the inherent network factors (e.g. the load of traffic, the delay, the jitter). These factors must be considered when the quality of control techniques are applied. By using an on line adaptation of quality of control and some other techniques, we analyze the behavior of the control systems when the control loop includes multi hop paths. Simulation results show the effects of delay components derived from the multi hop paths of the control loop.

Index terms – Wireless Networked Control System, Online adaptation quality of control, Multi hop control system

1 Introduction

In Wireless Networked Control systems(WNCS), the quality of control (QoC), i.e., the performance delivered by each closed-loop operation, depends not only on the controller design but also on the quality of service (QoS) offered by the wireless network. The degradation of the QoC of the controlled process can be caused by the network or by the controlled system. In order to manage this QoC many researchers try to enhance the QoS offered to the WNCS. Thus several network resource allocation techniques for WNCS have been proposed. These techniques are based on static strategies that ensure average control performance at the expenses of permanently occupy the available bandwidth. In the case of wireless networks, the use of resources must be controlled at the same time that the control performance. We consider de case of a multi-hop IEEE 802.15.4/Zigbee network used within the control loop of a control system. We propose an adaptive online QoC management protocol : if the QoC of the controlled process is not sufficient, this network offers more resources to the WNCS. Moreover, since the degradation of the QoC can be due to the control loop, if there is no enhancement of the QoC for a certain amount of time, we have to act on the control loop (changing the sampling period for example). We analyze the degradation of the QoC caused by the lack of network resources and by the presence of multiple delay components derived from the multi-hop network configuration.

The remainder of the contribution is organized as follows. Section 2 shows the related contributions. Section 3 presents the model of the platform used as the controlled system. The multi hop network platform is described in Section 4. In Section 5 we describe the effects of different lengths of the control loop over the control system. We observe that the delay over the loop has a main influence over the control behavior. Section 6 describe several QoS mechanisms. In Section 7 we present an online adaptive mechanism applied over the multi hop network. Finally, Section 8 contains some concluding remarks.

2 Related work

Guaranteeing the network QoS, especially for industrial process control architecture, is a common problem that has been addressed in several research works. In [1], the case of a dedicated network (CAN, WIFI, IEEE 802.15.4/ZigBee) to the process control application has been studied but the realistic case with other nodes than control loop nodes sharing the network has not been analyzed. In [2], the suitability of IEEE 802.11b for wireless networked control system has been analyzed and it has been shown that the network bandwidth is important for the performance of WNCS.

Koubâa et al. [3] proposed a simple differentiated service scheme for slotted CSMA/CA in IEEE 802.15.4 to improve the performance of time sensitive message. In [4], the authors have modified the initial value of the backoff exponent in the IEEE 802.15.4 MAC (slotted CSMA/CA) and proposed an adapted backoff exponent (ABE) algorithm. These works was restrained to the slotted CSMA/CA and was not analyzed in the case of wireless networked control systems.

The blackburst mechanism [5] was introduced in the IEEE 802.11 to minimize the delay for real time traffic. Blackburst requires that all high priority stations try to access the medium with constant interval, and the ability to jam the wireless medium for a period of time. This mechanism was not designated for IEEE 802.15.4. Moreover, the length of the black burst is determined by the time the station has been waiting to access the medium and not by its priority.

Some other works have dealt with the IEEE 802.15.4/ZigBee and especially the synchronization of the GTS mechanism. Francomme et al. [6] proposed a new synchronization method for beacons and GTSs in meshed networks using IEEE 802.15.4. Koubâa et al. [7] proposed a synchronization mechanism based on time division beacon scheduling to construct cluster-tree WSNs. Moreover, they proposed a methodology for an efficient duty-cycle management in each router to ensure the fairest use of bandwidth resources. Those works are centric over network Quality of Service (QoS) and do not include any actual real-time applications.

These works show that the differentiation of service is a promising solution to guarantee the QoS required by the network and so the QoC needed by the control loop.

There are several works which deal with the resource allocation for control loops. Marti et al. [8] studied the CPU resource management and showed that by using feedback to dynamically allocate resources to controllers as a function of the current state of their controlled systems, control performance can be significantly improved. They present an optimal resource allocation policy that maximizes control performance within the available resources. In this work the QoC management depends on the controller since when there is a perturbation, the sampling period is adapted.

Velasco et al. [9] propose a dynamic approach to bandwidth management in networked control systems that allows control loops to consume bandwidth according to the dynamics of the controlled process meanwhile attempting to optimize overall control performance. This is done by augmenting the original state-space representation of each controlled system with a new state variable that describes the network dynamics.

Ji et al. [10] assign the network-bandwidth dynamically to each control loop according to the quality of performance of each control loop. This is done by using an adaptive controller.

All these works try to adapt the control loop to its environment. Thus, the parameters of the control loop are changed, especially the sampling period.

Marti et al. [11] propose an approach to adaptive controllers for NCS that online adapts the control decisions according to the dynamics of both the application and the executing platform. This approach offers capabilities for dynamic management of QoC through message scheduling. They formulate a scheduling strategy that uses feedback information from the control application in order to schedule messages in such a way that the degrading effects of the message latencies are minimized. Thus, the overall QoC is improved. However, this strategy was not analyzed nor tested.

All above works are designed for wired networks. For the best of our knowledge, there is no QoC online adaptive strategy for WNCS using the IEEE 802.15.4 which adapts the QoS of the network to the control loop requirements. This QoS management can be done through the service differentiation as stated above.

In this paper,first, the WNCS using the probabilistic priority, the deterministic priority and the GTS mechanism are analyzed in order to ensure the QoC of the controlled system. Then, an online adaptive scheme is proposed for wireless networked control systems.

3 Platform description

The platform function is to move a metallic bar along a linear rail. This platform consists on two independent mobile carts. Each cart is equipped with measurement sensors, calculators and communication devices. There is also a computer used for IHM, supervision and high level control law calculation algorithms.

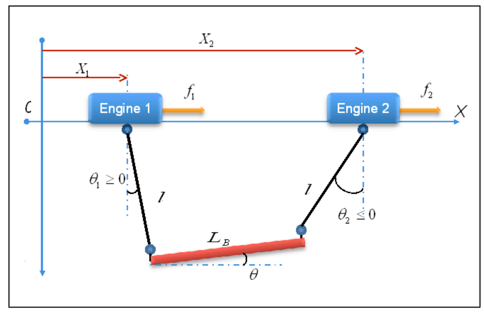


FIG. 1 – Platform description

The system has four freedom degrees : X_1, X_2, θ_1 and θ_2. After linearization, the system model is given by

$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx \end{cases} \quad (1)$$

where

$$\begin{cases} x = [X_1, X_2, \theta_1, \theta_2, \dot{X}_1, \dot{X}_2, \dot{\theta}_1, \dot{\theta}_2] \\ u = [f_1, f_2] \end{cases}$$

$$A = \begin{pmatrix} 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & k_1 & -k_2 & -k_3F_v & k_4F_v & k_5C_v & -k_6C_v \\ 0 & 0 & -k_2 & k_1 & k_4F_v & -k_3F_v & -k_6C_v & k_5C_v \\ 0 & 0 & -k_7 & k_8 & k_9F_v & -k_{10}F_v & -k_{11}C_v & k_{12}C_v \\ 0 & 0 & k_8 & -k_7 & -k_{10}F_v & k_9F_v & k_{12}C_v & -k_{11}C_v \end{pmatrix}$$

$$B = \begin{pmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ k_3 & -k_4 \\ -k_4 & k_3 \\ -k_9 & k_{10} \\ k_{10} & -k_9 \end{pmatrix}$$

and

$$C = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \end{pmatrix}$$

.

This platform is characterized by :

– k_i, $i = 1 \ldots 10$: system's constants which are calculated using the system's parameters,
– F_v : the viscous friction of engines 1 and 2 on the linear axis,
– C_v : the viscous friction torque on the bars of connection 1 and 2.

The control law is given by $u = -Kx + HX_{ref}$ with

$$K^T = \begin{pmatrix} 37.42 & 0 \\ 0 & 37.42 \\ -124.99 & -7.05 \\ -7.05 & -124.99 \\ 55.17 & 5.72 \\ 5.72 & 55.17 \\ -36.03 & 1.54 \\ 1.54 & -36.03 \end{pmatrix}$$

and

$$H = \begin{pmatrix} 37.42 & 0 \\ 0 & 37.42 \end{pmatrix}$$

.

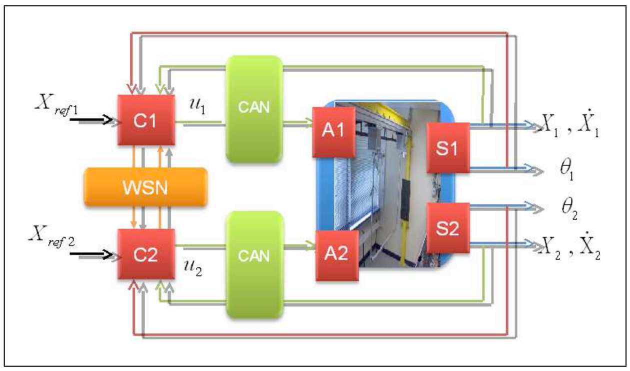


FIG. 2 – Networked control system architecture

Using simulations, the maximum value of the sampling period is $40ms$ in order to keep the system stable.

4 The network platform

The IEEE 802.15.4 defines two type of network components : the Full-Function Devices (FFD) and the Reduced-Function Devices (RFD). The FFD can work as a router, a bridge or a Personal Area Network (PAN) coordinator. The RFD are the minimum form of the IEEE 802.15.4 devices with minimal functionalities (usually they are used as sensor nodes) and minimal energy consumption. There are three routing types in Zigbee :

– Star topology routing, defined by a coordinator and several end-devices.
– Tree topology routing, defined by a hierarchical routing composed by several end-devices and one or more FFD.
– Mesh topology routing, where the routing strategy is more complex than in the tree or star topologies. This topology enables to establish routes between any pair of network devices allowing different routes.

In our testbed we use a set of Crossbow Micaz motes working on the 2.40-2.48 GHz band with support for the IEEE 802.15.4/Zigbee standards and offering a 250kbps transmission data rate. The motes use the ATmega128L running at 8MHz. Each component of the network use a micaz as a communications interface. The IEEE 802.15.4/Zigbee network transport the traffic originated at each location using one or more FFDs in any network configuration. A pair of AA batteries provide energy to the FDDs, the other network components use the conventional energy source (from communications port at each location). A simple routing policy allows to communicate the components of the network : sensor, actuator, controller and other devices. The network aims to provide a minimal performance to satisfy the required Quality of Control (QoC) of the control system. This requirements are translated in network terminology as the guaranteed Quality of Service (QoS). Must of the times, this QoS can be expressed in terms of end-to-end delay and delivery rate. We implement a multi-hop routing policy in order to find the relationship between the QoC/QoS requirements and the network parameters. The network can be implemented by using any of the three IEEE 802.15.4/Zigbee routing types. The objective of this testbed is to determine the parameters of a network making part of a control loop. A relationship between network behavior (end-to-end delay, delivery rate, energy efficiency, etc) and control (system response, lost packets tolerance, etc.) parameters can be establish and the compromise between requirements of control and the routing strategy can be derived.

5 Model description and routing effect

In our example, the communication channel is shared by 2 cyclops (sensors equipped with camera) and a main control unit as shown in Figure 3. Hence, the wireless network is used to transmit image packets from cyclops to the main control unit. The image sensor has CIF resolution (352 × 288). Each cyclops sends, periodically, 133 $bytes$. Besides, there are other nodes which contribute in the routing process between the two calculators. Thus, we can study the one-hop and multi-hop routing.

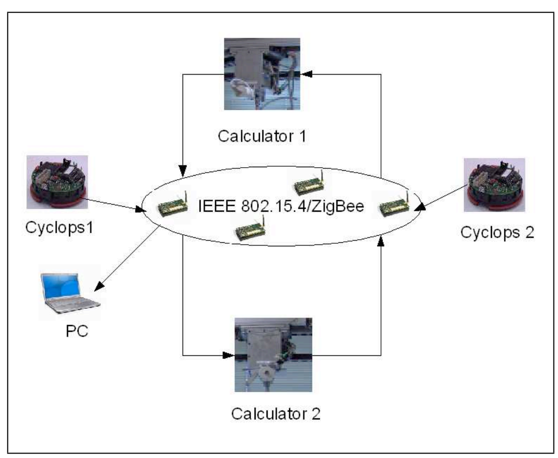
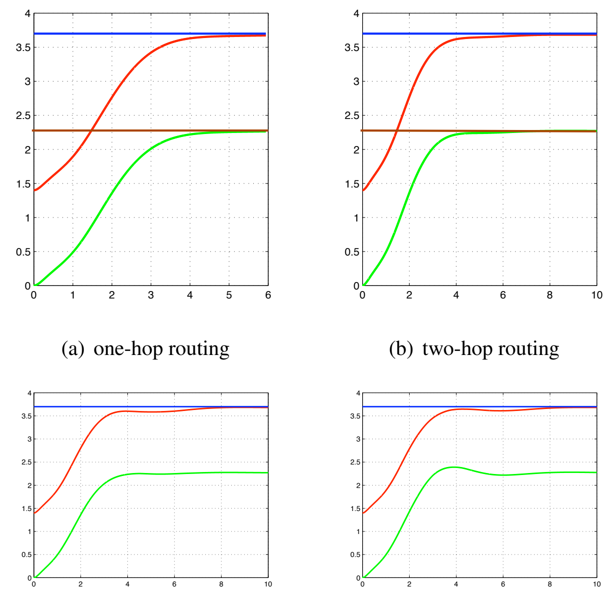


FIG. 3 – Platform description

The studied system is composed of two calculators whose control law is dependent since needs each other information. In this part, we focus on the influence of the chosen paths on the controlled carts. There are two possible situations. The first one consist on the same number of hop in the each path. The second situation considers that the number of hops of each path is different.

The first set of simulations deals with the same number of hops in each path. Different cases are presented : 1, 2, 3 and 4 hops. The simulation results using the IEEE 802.15.4 shows that the multi-hop routing induces the degradation of the QoC. In fact, as shown in Figure 4, for the same configuration, the WNCS which uses the one-hop routing reaches the stability quicker than when it uses the multi-hop routing. Besides, the responses of the two carts behave in the same way all the time. This can be explained by the same delay values. In fact, since the number of hop is the same in each path, the induced delay is the same for the two carts. Thus, the two carts are synchronized.



(a) one-hop routing (b) two-hop routing

(c) three-hop routing (d) four-hop routing

FIG. 4 – results when using IEEE 802.15.4 and multi-hop routing with overloaded network

The second case deals with different number of hops between each path. Figure 5 shows the responses of the two carts the path from the calculator 1 to the calculator 2 is composed of only one hop whereas the one from the calculator 2 to the calculator 1 is composed of four hops. These responses are no longer synchronized since the delays caused by each path are different.

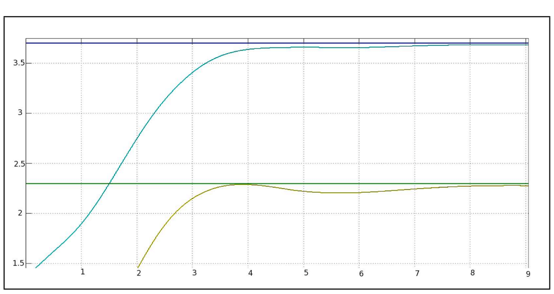


FIG. 5 – Platform description

Given that the communications paths between calculators are different, each one has a different associated delay derived from multiple hop paths between components of the wireless network making part of the control system. When both delay components are equivalent, a slower response from the control system is obtained and the stability state is reached later. In this case, the equivalence of delays allows the system to have a synchronized response over both carts. When the system has two different components of delay, the response of the system performance may be unsatisfactory.

6 QoS adaptation

In this paper several QoS adaptation mechanisms are proposed and implemented in the TrueTime package.

6.1 Black burst mechanism

The goal of black burst [5] is to minimize the delay for the real-time traffic. The black burst mechanism requires that :(i) all stations try to access the medium with equal, constant interval, blackburst period ; (ii) the ability to jam the medium for a period of time. When a new cycle starts, each station who wants to send a frame, sends a blackburst to jam the channel. The length of the blackburst is determined by the priority of the application, and is calculated as a number of black slots. The duration of a black slot t_{bslot} is at least equal to the turn around time (TT) ($t_{bslot} \geq TT$). After transmitting the blackburst, the station listens to the medium for an observation time t_{obs} ($t_{obs} < t_{bslot}$) to see if another station is sending a longer blackburst. This would imply that this station has higher priority, so it should access the medium first. If the medium is idle, the station will then send its frame, otherwise it will wait until the medium becomes idle again and enter another black burst period. As it is supposed that there is different priority for each station, the black burst mechanism will yield to a unique winner.

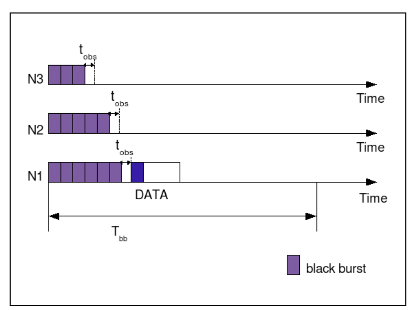


FIG. 6 – Competition to access to the communication medium

Figure 6 shows three nodes competing to access to the communication medium. Node $N3$ has the lowest priority, thus it is the first one to finish the transmission of black burst. Then, it listens to the medium during a t_{obs} and it finds that there is someone else sending. Hence, $N3$ quits. The same thing for node $N2$. When node $N1$ (with the highest priority) transmits its black bursts and then listens to the medium, it finds it free. Thus, $N1$ is the winner and start to send its data packet.

6.2 Adaptive priority

The second QoS adaptation mechanism is based on the adaptive priority [7]. This is ensured through a priority mechanism which adapts the backoff exponent value in the IEEE 802.15.4 MAC standard.

The CSMA/CA mechanism for IEEE 802.15.4 uses the random waiting delay for collision avoidance. It uses the backoff exponent (BE) which is related to how many backoff period (BP) a device must wait before attempting to assess the channel activity. The algorithm attempts to avoid collision by waiting during a given delay randomly generated in the range of $[0, 2^{BE} - 1] \times BP$. If battery life extension is activated then, $BE = min(2, macMinBE)$ else, $BE = macMinBE$ where macMinBE attribute specifies the minimum of backoff exponent, which is set to 3 by default. This aspect is exploited in order to differentiate the services offered by the WSN. We propose to vary the randomly generated waiting delay depending on the priority of the packet. Thus, by choosing a higher macMinBE for the applications, different from the control loop, the probability to have a longer delay is increased and the control loop nodes will be able to send their data packets.

The nodes are divided into two classes : the high priority (h) class contains the nodes of the WNCS (sensor, controller, and actuator), and the low priority (l) class is composed of the other nodes present in the WSN. BE_{CL} represents the BE of the control loop nodes $macMinBE_{CL}$ its $macMinBE$, and it is set to the default value 3. The $macMinBE_{OA}$ and BE_{OA} are the $macMinBE$ and the BE of the other applications sharing the WSN. When the batterylife extension is not activated, the control loop nodes have to wait $random[0, 2^{BE_{CL}} - 1] \times BP$ ($random[0, 7] \times BP$).

The $macMinBE_{OA}$ of the low priority nodes is increased in order to make their data packets wait during a delay randomly generated in a longer range. The intersection between the waiting ranges of the high and low priority nodes is eliminated as shown in Figure 7. The lower-priority applications will wait during a delay randomly generated in the range of $[variable, 2^{BE_{OA}} - 1]$ backoff periods. The question is how to choose the $variable$'s value. This variable is set to $2^{BE_{CL}}$ so that there is no collision between the members of the two classes ($variable = 8$).

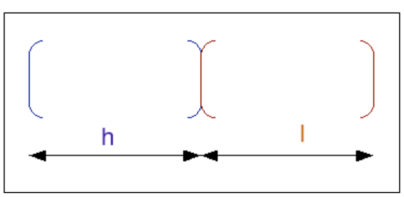


FIG. 7 – Waiting ranges for high (h) and low (l) priority nodes using the deterministic priority

6.3 QoS adaptation : CSMA/CA with priority

The CSMA/CA mechanism for IEEE 802.15.4 uses the random waiting delay for collision avoidance. It uses the backoff exponent (BE) which is related to how many backoff period (BP) a device must wait before attempting to assess the channel activity. The algorithm attempts to avoid collision by waiting during a given delay randomly generated in the range of $[0, 2^{BE} - 1] \times BP$. If batterylife extension is activated then, $BE = min(2, macMinBE)$ else, $BE = macMinBE$ where macMinBE attribute specifies the minimum of backoff exponent, which is set to 3 by default. This aspect is exploited in order to differentiate the services offered by the WSN. We propose to vary the randomly generated waiting delay depending on the priority of the packet. Thus, by choosing a higher macMinBE for the applications different from the control loop, the probability to have a longer delay is increased and the control loop nodes will be able to send their data packets.

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6.4 GTS mechanism

To ensure the stability of the WNCS, we are interested in the beacon-enabled mode of the IEEE 802.15.4. Indeed, network resources are reserved using the GTS mechanism. The superframe duration (SD) is given by
$SD = aBaseSuperframeDuration.2^{SO}$
for $0 \leq SO \leq BO \leq 14$
where SO is the Superframe Order.

SD is divided into 16 equally-sized time slots, during which frame transmissions are allowed. GTSs are allocated by the PAN coordinator. The PAN coordinator can allocate at most seven GTSs and each GTS may occupy more than one time slot.

Each node in the control loop will have a reserved GTS whose size will be 1 slot since the control data is not big (small frame). Figure 8 shows that 3 GTSs (3 slots) are needed, but as the superframe has at least 16 slots (if the inactive part is omitted), the WNCS sampling period T_e has to be at least equal to the superframe duration. Indeed, T_e must be greater than SD. As the smallest superframe duration (for $SO = 0$) is equal to $0.01536s$, then the WNCS sampling period T_e is greater then $T_{e_{min}} = 0.01536s$. Besides, since the number of GTS is restricted to 7, the GTS mechanism cannot afford QoS guarantees to more than two control loops with the same sampling period. Otherwise, one should use the scheduling policy in [6].

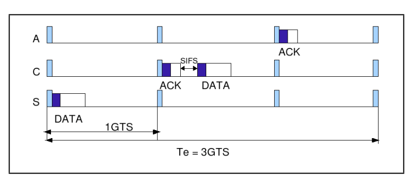

FIG. 8 – Used GTSs by the WNCS

Moreover, the sensor and the controller use only CFP to send sensing and control data so that they do not use the CAP part. The CAP part is used by other nodes using the WSN.

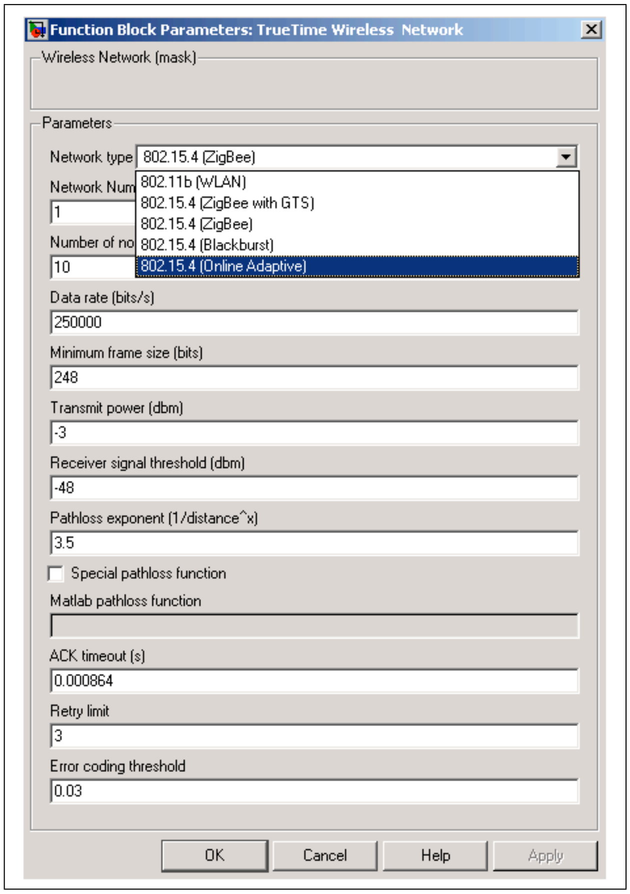

FIG. 9 – TrueTime wireless network block

6.5 Discussion

These mechanisms are efficient when there is only one WNCS and the path is composed of one hop as shown in [12] and in [13]. However, the co-existence of several WNCSs induces a conflict between the messages of these WNCS. For example, in the case of the double cart, the packets of the two controlled carts have the same priority. Thus, collisions may happen between these packets. Besides, multi-path routing can be a source of conflict since if there are different instances of the same WNCS message, it may cause a collision between them. This kind of problem can be avoided if the network delay is less than the sampling period.

7 QoC online adaptation

The QoC of the WNCS is evaluated using the controlled process error e. If the WNCS is stable, the error is bounded. Thus, the same criterion, as in [10], is adopted : the error should be bounded by a threshold to ensure the required QoC to the plant. This threshold depends on the controlled process and on the reference value if there is any. If $e > threshold$, the WNCS is considered to be in a critical situation and action has to be taken. The trouble is caused either by the controlled system itself or by the network (overloaded network). Action should be taken on the network for a certain period of time through offering more resources to the WNCS. If the situation is not improved (there is a problem in the control loop), action should be taken on the WNCS by changing the sampling period for example. In order to enhance the QoC this work deals with the adaptation of the QoS.

For the systems with architecture presented in Figure 10, the error e is equal to $|r - y|$ where r is the reference and y is the process response. In order to have a good QoC, the condition is

$$|r - y| < threshold + r \tag{2}$$

has to be satisfied. The reference value is added in order to take into account the case where there is a change in the reference value that makes $|r - y| = r$ and there is no network problem.

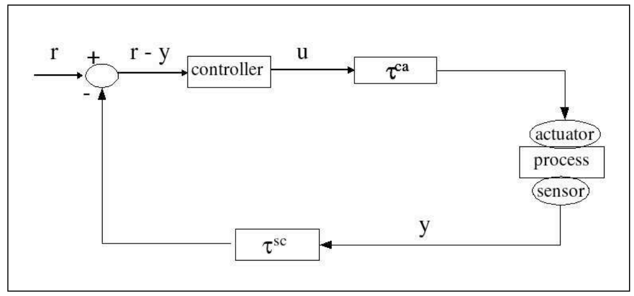

FIG. 10 – The network control system architecture

7.1 Dynamic management of the QoC

The QoC of the controlled process is dynamically managed through the QoC metric e (the system error). First, the controller checks the error value so that it can decide its priority level because there are two : the maximum priority, and the normal one. If the error e is higher than the threshold, then the WNCS is in critical situation. Thus, the controller priority is set to its maximum value. Else, the controller has a normal priority. This priority data is expressed through the random range of the waiting delay of the CSMA/CA. There are two alternatives :

1. this range is set to a big one for all the nodes in the network, then when the controller priority is equal to the maximum value, this range is decreased for both the sensor and the controller,
2. this range is set to the default one for all the nodes, then if the controller priority is equal to the maximum value, this range is increased for all the nodes in the network except the sensor and the controller.

The first solution is the most suitable for hard real-time applications considering the robustness aspect. However, it induces the waste of the network resources by the large waiting delay. Thus, the second solution is adopted.

The priority parameter is transferred to the MAC layer which will send it to the WSN coordinator. This coordinator is in charge of informing all the other nodes of the current controller's priority. Once one node gets the controller priority information, it decides if it will apply the CSMA/CA either with the probabilistic priority or without. This decisions is related to the controller priority value. Moreover, the transition between the two mechanisms is done progressively. In fact, if the controller priority is equal to the maximum value, the range of the random delay is increased, else, it decreased until it is equal to the default range.

7.1.1 Online probabilistic priority adaptation

Action will be taken on both the $variable$ and $macMinBE_{OA}$. Moreover, since a static assignment of these variables can lead to the under-use of the network resources due to the large waiting delay, these variables are adapted online depending on the controller's priority level. Thus, if the control loop is in a critical situation, the $variable$ is set to 8 and the $macMinBE_{OA}$ is increased by 1 in order to enlarge the waiting delay, else the $variable$ is set to 0 and the $macMinBE_{OA}$ is decreased by 1.

The QoS management depends on the QoC metric which is represented by the controlled system error. Thus, the upper bound of the allowed error ($e \leq threshold$), the threshold, has to be chosen carefully. This threshold is defined, in equation 3, by the control loop threshold ($threshold_{process}$) and a $security\_margin$.

$$threshold = threshold_{process} - security\_margin \quad (3)$$

The delay introduced by the network should be taken into account in order to make the new QoS effective. This delay represents the propagation time of the new priority value to all the nodes. Thus, the network delay is calculated as

$$d_{net} = max(RB) + aBaseSuperframeDuration \cdot 2^{BO}, \quad (4)$$

when $BO = 0$, $d_{net} = 17.6ms$.

The minimal sampling period $T_{e_{min}}$ of the control loop has to be as the following : $T_{e_{min}} = d_{net}$ so $T_{e_{min}} = 17.6ms$.

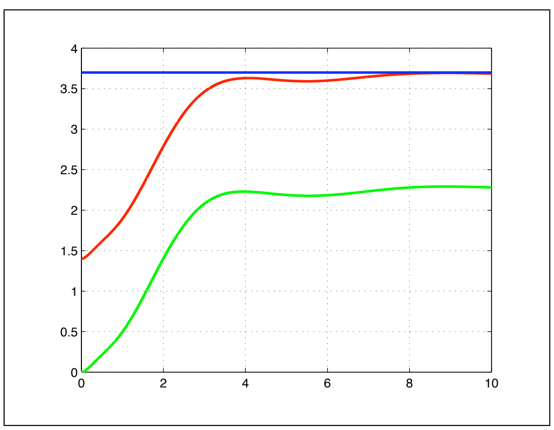

FIG. 11 – results when using Online adaptation and multi-hop routing 1

8 Conclusion

The application of the techniques for enhancing the QoC over networked control system may consider the behavior of network and its inherent aspects. In this study case, the presence of a wireless network causes the delay and packet loss so that the QoC of the controlled system is badly affected. When a multi hop control system is used, other factors must be taken into account in order to guarantee the required levels of QoC. Some other techniques related to the network resources management or routing parameters can be foreseen in order to improve control systems. The use of the network delay as control

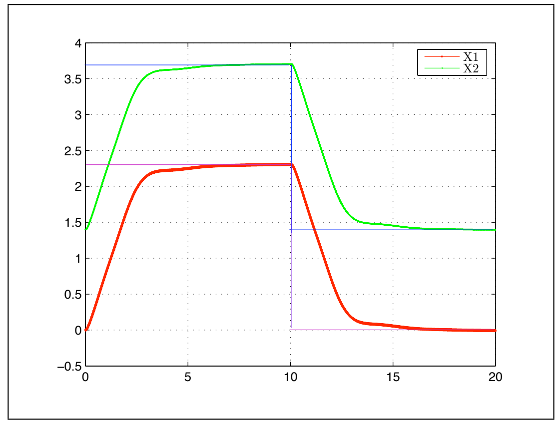

FIG. 12 – Results when using Online adaptation and multi-hop routing 2

parameter and other open issues will be investigated in future work.

This work is in progress under the CONECS and COW-NECS projects.

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