# Wireless Networked Control System using IEEE 802.15.4 with GTS

Najet Boughanmi, Ye-Qiong Song, Eric Rondeau

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Najet Boughanmi
LORIA-CRAN-INPL
boughanm@loria.fr

YeQiong Song
LORIA-INPL
song@loria.fr

Eric Rondeau
CRAN
eric.rondeau@cran.uhp-nancy.fr

## Abstract

*In this paper, the suitability of wireless sensor networks for networked control loop is shown. As the non beacon-enabled mode of IEEE 802.15.4/ZigBee does not ensure the stability for the control loop since non mechanism can prevent the perturbation coming from other applications sharing the same network, we investigate the beacon-enabled mode using the Guaranteed Time Slot (GTS) mechanism and show it is suitable* [1] .

## 1. Introduction

Networked Control Systems (NCS) [9] are getting an increasing interest from both industrials and researchers. However, they suffer from limitations in mobility and flexibility because of the network wires. Wireless Networked Control Systems (WNCS) are an alternative to overcome this problem since they offer easier configuration and maintenance especially in case of several networked control loops and in shared communication medium. RUNES project [1] has been interested in it and showed its importance.

The IEEE 802.15.4/ZigBee seems to be one of interesting wireless networks comparing to the others since it is a low-cost low-power Wireless Sensor Networks (WSN). Moreover, even an industrial standard as WirelessHART [2], which was designed to meet the requirements of wireless networks operating in process plant, uses IEEE 802.15.4-based Physical layer and MAC PDU.

However, the IEEE 802.15.4/ZigBee with non beacon-enabled mode suffers from random delays, frame losses and limited data rate. The beacon enabled-mode in IEEE 802.15.4/ZigBee can offer real-time guarantees by means of the GTS mechanism. Hence, using the beacon enabled mode makes IEEE 802.15.4/ZigBee suitable for implementing closed-loop for real-time systems. In this paper, we investigate the capacity of IEEE 802.15.4/ZigBee to support closed control loops applications. The impact of network performance variations is evaluated in terms of Quality of Control (QoC). In particular, we show the limits of IEEE 802.15.4/ZigBee: the lower bound of the sampling period of the control loop is $0.01536s$, the number of control loops is limited to two. We give a guideline to configure network parameters to meet QoC requirement of a control loop. Often, one needs to simulate the process, the control and the wireless network. There are several tools which allow the co-design of control loops and networks. We are using TrueTime [8], a Matlab/Simulink simulator since it allows us to simulate the temporal aspects of multi-tasking real-time kernels and wireless networks within Simulink together with the continuous-time dynamics of the controlled plant. TrueTime does not implement the beacon-enabled mode of IEEE 802.15.4/ZigBee. So, we added this mode to TrueTime in order to study the effect of the GTS mechanism on wireless networked control systems. This package can be downloaded at http://www.loria.fr/equipes/TRIO/packageGTS.zip.

This paper is organized as follows. In Section 2 related works are discussed. Then, the considered NCS is described in Section 3. A brief overview of the IEEE 802.15.4/ZigBee is presented in Section 4. Section 5 deals with an analysis of the effect of the non beacon-enabled mode on WNCS. Then, in Section 6 we give the proposal and the results.

## 2 Related work

Guaranteeing network QoS, especially for industrial process control architecture, is a common problem that has been addressed in several research work. In [7], 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 analysed. In [3], the suitability of IEEE 802.11b for wireless networked control system has been analysed and it has been shown that the network bandwidth is important for the performance of WNCS.

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Some other works have dealt with the IEEE 802.15.4/ZigBee and especially the synchronization of the GTS mechanism. Francomme et al. [5] proposed a new synchronization method for beacons and GTSs in meshed networks using IEEE 802.15.4. Koubâa et al. [6] 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.

All these works show that IEEE 802.15.4/ZigBee with GTS mechanism is a promising solution to guarantee the QoS required by the network and so the QoC needed by the control loop. Thus in this work we will analyse the WNCS using the beacon-enabled mode of IEEE 802.15.4 than we will present the non beacon-enabled mode as a way to ensure the stability of the WNCS.

## 3 The considered networked control system

Our system consists on a cart whose movement is guided along a rail [4]. We aim to control the cart's position. The variable characterizing the system's state $\left(x^T = \left[\begin{array}{cc} d & \dot{d} \end{array}\right]\right)$ are: $d$, the cart position along the rail measured from a reference point, and, $\dot{d}$ its velocity. We introduce a wireless sensor network containing the sensor (S), the controller (C) and the actuator (A) as shown in Figure 1. The network add new delays: $\tau^{sc}$ is the delay between the sensor and the controller, and $\tau^{ca}$ is the delay between the controller and the actuator ( Figure 2). The controller behaviour is characterised by the transfer function $G_C(s)$ and the process (the cart here) by $G_P(s)$. $U(s)$ is the command, $E(s)$ the error , $Y(s)$ the system response, and $R(s)$ is the reference.

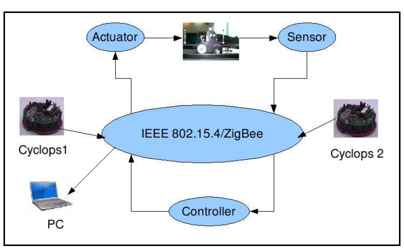


**Figure 1. IEEE 802.15.4/Zigbee using CSMA/CA: shared network**

The sampling period should be higher than $0.010s$ [4]. We are going to study the impact of the network's performance on the controlled system in both ideal and realistic cases and how resolve the problems if there is any.

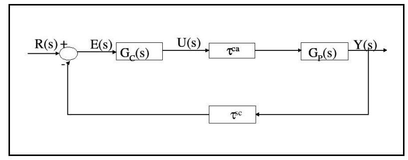


**Figure 2. The networked control system architecture**

## 4 IEEE 802.15.4/ZigBee protocol overview

The MAC protocol supports two operational modes that may be selected by the coordinator: beacon-enabled mode and non beacon-enabled mode.

- Non beacon-enabled mode : Medium access control is provided by an unslotted CSMA/CA (Carrier Sense Multiple Access/ Collision Avoidance) mechanism (using a random backoff time based on backoff period and Backoff Exponent (BE). There is no priority mechanism so no way to isolate a particular flow among all traffic.

- Beacon-enabled mode : Beacons are periodically sent by Zigbee coordinator to synchronize nodes that are associated with it, and to identify the Personal Area Network (PAN). Superframe is contained between two consecutive beacon frames. The superframe structure is used to manage communication between these devices. The superframe contains a Contention-Access Period and Contention-Free Period (CFP), and it may include an inactive period.

## 5 Analysis of the WNCS using the non-beacon enabled mode of IEEE 802.15.4/ZigBee

### 5.1 Ideal case: dedicated WSN

The entire communication channel is dedicated to the control loop. The distances between sensor, actuator and controller are small enough so that they can receive the signals from each other.

In [7], the lower bound for the sampling period $T_e$ for IEEE 802.15.4 (non beacon-enabled mode) was evaluated as follows :

$$\begin{aligned} T_e \quad \geq \quad & \text{Random backoff duration } (Rand[0, 2^3 - 1] * 320\mu s) \\ & + \text{Data frame duration } (352\mu s) \\ & + \text{Turn around Time (TT) } (192\mu s) \\ & + \text{ACK frame duration } (160\mu s) \\ & + \text{Short Inter-Frame Space (SIFS) } (192\mu s) \\ & + \text{Random backoff duration} \\ & + \text{Data Frame duration} \\ & + TT + \text{ACK Frame duration} + SIFS. \qquad (1) \end{aligned}$$

Figure 3 shows flows in a sampling period. The limit of the sampling period was calculated equal to $6272\mu s$[2].

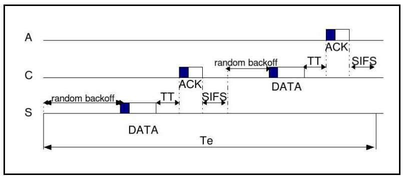


**Figure 3. Flows in a sampling period IEEE 802.15.4/Zigbee non beacon-enabled mode**

Figure 4 shows the behaviour of the plant Y (cart) and the reference R. We notice that the plant follows instantaneously the reference and it is stable.

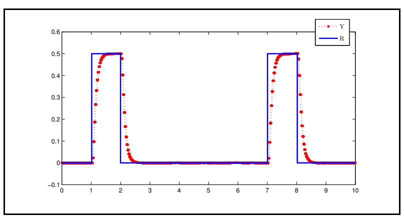


**Figure 4. IEEE 802.15.4/Zigbee using CSMA/CA in ideal case**

### 5.2 Realistic case: shared WSN

In practice, it is not reasonable to dedicate the entire communication channel to the control loop. In fact, the communication channel is shared by 2 cyclops (sensors equipped with camera) and a main control unit as shown in Figure 1. 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, a message of $1064$bits In the following, we will study the plant behaviour for different perturbation load. We change the transmission period to see the effect of the new additional network load on the NCS. Our NCS can stay stable if the additional network load is less than $44\%$ of the total bandwidth. However, if this additionnal network load reaches $44\%$ ( the transmission period of each cyclops $= 0.02s$), the cart becomes instable as shown.

[2]We notice that it is different from the one in [7] ($7040\mu s$).

## 6 Our proposal

To ensure the stability of the WNCS, we are interested in the beacon-enabled mode of the IEEE 802.15.4. Indeed, we will reserve network resources 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 5 shows that we need 3 GTSs (3 slots), but as the superframe has at least 16 slots (if we omit the inactive part), the WNCS sampling period $T_e$ has to be at least equal to the superframe duration. Indeed, we have to ensure that $T_e \geq SD$. As the smallest superframe (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. Otherwise, one should use the scheduling policy in [5].

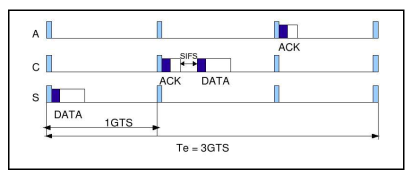


**Figure 5. Used GTSs by the WNCS**

Moreover, the sensor and the controller use only the 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.

We developed the beacon-enabled mode of the IEEE 802.15.4/ZigBee in TrueTime. Figure 6 shows it's network parametrization.

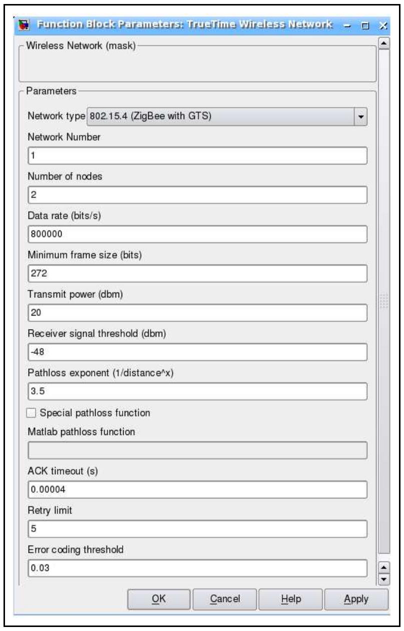


**Figure 6. The IEEE 802.15.4/ZigBee with beacon enabled mode in TrueTime**

## 6.1 Simulation and results

We consider the system shown in Figure 1. We simulate this system using the IEEE 802.15.4/ZigBee beacon-enabled mode. Moreover, in these simulations we disabled the mechanism of signal adaptation since it creates messages and disturbs the GTS mechanism (we will need more than one GTS for each node). Besides, we use only two GTS, one for the controller and another for the sensor because, in TrueTime is not necessary to send ACK messages.

We made the assumption that there is no energy problem for the nodes (infinite amount of energy). Moreover, we consider that the controller is the PAN coordinator. We do not address the mobility problem (nodes are static) for the moment. Besides, in the simulation example, we do not take the acknowledgement into account. So we only need two GTSs. The nodes send only in their reserved GTS and without packet loss.

We tested several perturbation's loads which are higher than $44\%$, and we had the result shown in Figure 7. The plant behaviour follows almost exactly the reference. Thus, using the GTS mechanism guarantees the network QoS and the required QoC for the control loop.

# 7 Conclusions

GTS is an interesting mechanism for critical real-time systems. We implemented it in TrueTime so that we can

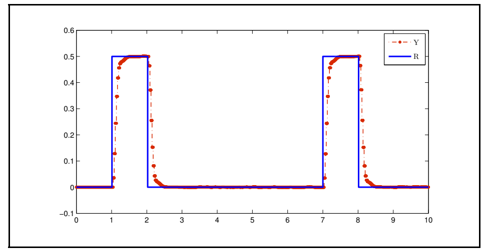

**Figure 7. Results with IEEE 802.15.4 using GTS**

evaluate the WNCS and other researchers can use it. This mechanism can be used only for control loop with sampling period greater than $15,36ms$. Moreover, WNCS with a sampling period less than the smallest given here can not use this mechanism. However, since the number of GTS is restricted to 7, we need to study the case where we have more than 3 control loops sharing the same WSN. This study must be continued by considering energy and mobility problems and the impact of channel error on the stability of WNCS using GTS.

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