

Self-Triggered Control for Industrial Wireless Sensor and Actuator Networks

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Abstract—Energy and communication bandwidth are scarce resources in wireless sensor and actuator networks. Recent research efforts considered the control of physical processes over such resource limited networks. Most of the existing literature addressing this topic is dedicated to periodically sampled control loops and scheduled communication, because it simplifies the analysis and the implementation. We propose instead an aperiodic network transmission scheme that reduces the number of transmission instances for the sensor and control nodes, thereby reducing energy consumption and increasing network lifetime, without sacrificing control performance. As an added benefit, we show the possibility of dynamically allocating the network bandwidth based on the physical system state and the available resources. In order to allow timely, reliable, and energy efficient communication, we propose a new co-design framework for the wireless medium access control, compatible with the IEEE 802.15.4 standard. Furthermore, we validate our approach in a real wireless networked control implementation.

I. INTRODUCTION

Increasingly, control systems are operated over large-scale, networked infrastructures. The use of wireless communication technology provides major advantages in terms of increased flexibility, and reduced installation and maintenance costs. Following this trend, several vendors are introducing devices that communicate over low-power wireless sensor networks (WSNs) for industrial automation and process control. While WSNs have been widely analyzed and deployed to extract information from the physical world [1], actuation over wireless networks is still taking its first steps. We are interested in the use of wireless sensors and actuator networks to control the behavior of systems like irrigation networks of open water channels [2], where water flow is regulated by gates along the channels, and energy efficient buildings [3], where sensors are deployed to adjust heating, ventilation and air conditioning (HVAC) and illumination. And in particular, our foremost concern is how to efficiently design and implement such control systems to extend the life span of the wireless nodes.

An extensive set of tools and techniques have been developed to reduce power consumption in WSNs [4]. Unfortunately, the situation is much less favorable for wireless sensor and actuator networks (WSANs). While much work has been devoted by the controls community to the study of wired networked control systems, not so much attention has been devoted to the specific problems arising in the wireless

context. Traditional control engineering does not consider implementation requirements such as the minimization of communication between sensors, controllers and actuators. Such minimization in a large-scale wireless context is crucial both for energy savings and bandwidth reduction. Existing studies on this topic either neglect the dynamics of the physical system [5], [6] or do not provide guarantees on the stability of the physical systems being controlled [7]. In particular, most efforts of the network control systems community have been conducted under the assumption of periodic sampling and actuation [4], which in general may require data rates not practical in a wireless system. To address these issues, two new control paradigms have been recently proposed to efficiently use the communication resources in an aperiodic manner while enforcing pre-specified control performance. Event-triggered control [8], [9], [10], [11] monitors the state of the plant to select the time instants at which the control input needs to be updated. Unfortunately, since continuous monitoring of the state is required, the sensor nodes need to be awake and computing unceasingly, with the corresponding cost in terms of energy. Moreover, scheduling analysis for the network is in general not possible since the transmission times between the different nodes are not known in advance. Self-triggered control [12], [13], [14], [15] represents a model-based emulation of event-triggered control. Continuous monitoring of the plant is not needed and transmission times are provided in advance to allow for efficient scheduling. To the best of our knowledge, the only existing implementation of self-triggered control appeared in [16], where the control of a double integrator over a wired Controller Area Network (CAN) is considered. We present in this paper the first wireless implementation of self-triggered control. The wireless nature of the communication medium renders scheduling and energy considerations much more critical, and poses a set of new problems with respect to wired control. Hence, the present work represents a major step towards the design of resource-aware implementations of control laws over WSANs. We demonstrate the applicability of self-triggered control of a physical system over a WSAN and its advantages with respect to the traditional periodic paradigm, both in terms of energy savings and bandwidth reduction. For this matter, we propose the use of a modified low-power wireless IEEE 802.15.4

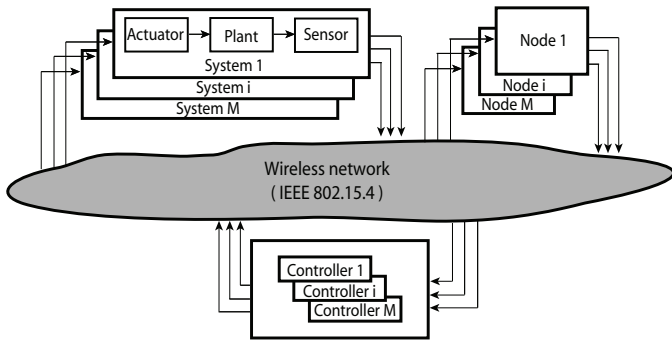


Fig. 1. Wireless Sensor and Actuator Network System Topology. Several control loops and independent sensors share information over the same low power wireless IEEE 802.15.4 network.

protocol [17] for the efficient implementation of self-triggered control. We have implemented the proposed design on a physical system composed of two coupled water tanks. The results presented in this paper show that for the considered physical system, protocol and scheduling policy, the self-triggered strategy reduces battery consumption in the sensor and actuator nodes by 41% with respect to a conventional periodic strategy. We believe this new technique has a remarkable potential as an implementation paradigm for wireless control systems.

II. CONTROL OVER WIRELESS NETWORKED SYSTEMS

We consider control systems of the form:

$$\dot{x} = f(x, u), \quad x(t) \in \mathbb{R}^n, \quad u(t) \in \mathbb{R}^m \quad (\text{II.1})$$

where x denotes the state trajectory of the control system and u the input trajectory. A feedback controller:

$$u = k(x) \quad (\text{II.2})$$

is designed to render the closed-loop system $\dot{x} = f(x, u)$ asymptotically stable. In wireless control systems, the controllers are not collocated with the plant but implemented on wireless nodes which communicate through the network with the sensors and actuators connected to the plant, sharing the same network with other independent nodes, as presented in Fig. 1. Whenever the control input needs to be updated, the wireless sensors connected to the plant sample the state x at time instant t_i and send a message (called sensor message) to the controller. Upon the arrival of this message, the control nodes compute the control inputs $u = k(x(t_i))$. When the computation is finished, the control nodes send a message to the wireless actuator nodes with the new input values u , which are applied to the plant (actuator message) at time $t_i + \delta$ where δ corresponds to the delay between measurement and actuation. We assume that the actuators hold the previous control input value until a new message from the controllers is received. The network is shared between the sensors, controllers, actuators and other independent nodes which might transmit information over the network in a periodic or aperiodic fashion. In this setup it is necessary

to determine the time instants at which the nodes need to exchange information in order to guarantee a desired level of performance. Moreover, given the energy and bandwidth constraints present in WSANs, we are interested in a strategy that minimizes the number of transmissions between nodes. In order to proceed, we first revisit a recent control paradigm that leads to a more efficient utilization of the available resources.

III. SELF-TRIGGERED CONTROL

As mentioned in the previous section, the input u cannot be updated continuously but only at discrete time instants t_i , whenever an actuator message is received. Traditionally, control-related messages are exchanged periodically, that is, $t_{i+1} - t_i = T$ for all $i \in \mathbb{N}_0$. The period T is chosen in order to guarantee stability and desired performance under all possible operating conditions. This approach represents a simple but conservative solution to the message scheduling problem since T has been selected based on a worst-case scenario.

However, it is known that control systems do not require the same amount of attention for every state of the plant. To take full advantage of this concept, new control paradigms have been developed. Event-triggered control decides the transmission times t_i according to the current state of the system $x(t_i)$. Typically, the loop is closed whenever a function h of the state reaches certain level; for instance, the transmission times t_i can be defined as follows:

$$t_i = \arg_t(h(x(t)) = 0)$$

where the function h is constructed based on the desired performance for the control system. This approach comes with two drawbacks. First, it requires continuous monitoring of the state and continuous evaluation of the triggering condition $h(x(t)) = 0$, which implies a considerable cost in terms of energy (since the sensor nodes need to be active all the time). Second, and most importantly, whenever $h(x(t)) = 0$ is satisfied the input needs to be updated immediately, that is, two messages (from sensor to controller and controller to actuator) need to be sent. Even if transmission and computation delays are ignored, at that time instant t_i the network might be not available. In other words, since we do not know the transmission times in advance, it is not possible to guarantee schedulability of the sensor and actuator messages.

Self-triggered control represents a model-based emulation of event-triggered control that overcomes the aforementioned drawbacks. Self-triggered implementations *identify* the time instants t_i at which the triggering condition is satisfied, taking into account the plant model given by (II.1), the last measurement of the state of the system $x(t_i)$ and the performance specification. The prediction of the time between two consecutive updates is embodied in the function:

$$\tau_i = t_{i+1} - t_i = g(x(t_i), S). \quad (\text{III.1})$$

Notice that under the self-triggered strategy continuous monitoring is no longer needed since the decision is based on the last measurement $x(t_i)$. Moreover, schedulability is now feasible since the next transmission time t_{i+1} is known at time

t_i . There exists several methods in the literature to compute such a function g [14], [13], [15]. In our practical implementation we used the techniques from [15]. Depending on the plant the techniques of [13], [14] might be more suitable (e.g., for nonlinear systems). Nonetheless, regardless the self-triggered technique chosen, the proposed overall system design and MAC mechanisms apply. Due to space constraints we do not explain here how such formula can be obtained, and we refer the interested reader to [15].

IV. WIRELESS COMMUNICATIONS

In this work we show the implementation of the self-triggered technique introduced in the previous section over a wireless network. The network protocol considered is the IEEE 802.15.4 [17], which specifies physical and medium access control (MAC) layers, and it is the base of solutions in industrial automation such as WirelessHART and ISA100 [1]. With respect to the physical layer, we follow the full specifications of the standard, while we suggest and perform modifications in the MAC layer in order to allow the implementation of control loops under the self-triggered control paradigm. The network topology in our study is a star network with all the messages going through a centralized coordinator node, called the PAN coordinator. This specialized node is assumed to be connected to a power supply with a large amount of energy, and is responsible for synchronizing and configuring all the nodes in the network. The IEEE 802.15.4 standard specifies two types of windows, active and inactive. The active period is further split into a Contention Access Period (CAP) and a Collision Free Period (CFP). During the CAP, the MAC scheme is Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) where the nodes in the network sense if the channel is busy before transmitting a message. The CAP period is used by nodes to send *best effort* messages where packet drops can happen due to collision or channel congestion. On the other hand, the CFP is intended to provide real-time guaranteed service, by allocating *Guaranteed Time Slots* (GTS) to the different nodes in the network, in a Time Division Multiple Access (TDMA) scheme. Since during the CFP there are no packet losses due to collisions or channel congestion¹, this mechanism is an attractive feature for time-sensitive wireless applications, as is the case of real-time control of several plants over a wireless network. Since this standard is designed for low-power applications, an *inactive period* is defined in the end of the active period so the network nodes and the PAN coordinator enter a low-power mode and save energy.

Contrary to the MAC defined in the IEEE 802.15.4 standard, where the assignment of GTS slots is done in a first-come-first-serve basis, we propose the use of a different scheduling mechanism. In our proposal, a scheduler node is responsible for the scheduling of GTS slots for the nodes in the network. This node is connected to the PAN coordinator, having access to all the information transmitted by the sensor nodes. In

¹We neglect wireless interference since we assume that there are no external nodes in the network using the same frequency bands.



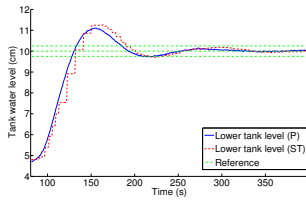
Fig. 2. Setup for the coupled water tank systems and the WSN.

order to allow for efficient usage of the available network resources, the messages transmitted by the nodes on the network will be scheduled according to an Earliest Deadline First (EDF) approach, which is known to be optimal for time-constrained schedules [18]. We consider two types of messages in the network, hard messages, (whose deadlines *must* be met) and soft messages (whose deadlines should be met). Control-related messages are considered to be hard, since missing their deadlines could cause instability or unacceptable performance. Since hard messages should always be scheduled before soft messages, the deadlines generated by the control-related messages (or any other hard message) are always smaller than the soft deadlines. Schedulability conditions have also been developed in the spirit of [19] for this protocol.

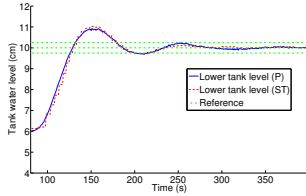
V. EXPERIMENTAL EVALUATION

In order to evaluate the performance of the proposed approach, we consider an industrial setting where a wireless network is shared by two control loops and several independent nodes transmitting soft messages. The control loops are regulating two coupled water tank systems from Quanser [20], where the tanks are collocated with the sensors and actuators and communicate wirelessly with a controller node. This system presents similar dynamical properties to irrigation networks of open water channels [2], where water flow is regulated by gates along the channels. The soft messages are monitoring messages with temperature, humidity and light values measured inside the room. Fig. 2 shows the setup of two water tank systems and the WSN with seven independent monitoring nodes.

We now briefly describe the details of the components of our networked control system. The wireless sensor platform chosen for this experiment is the Telos platform [21], commercialized as Tmote Sky/Telosb [22], [23]. The operating system used in the nodes is TinyOS [24]. The Coupled Water Tank system consists of a pump, a water basin and two tanks of uniform cross sections. The liquid in the lower tank flows to the water basin. A pump is responsible for pumping water from



(a) Coupled Tank System 1



(b) Coupled Tank System 2

Fig. 3. Evolution of the water level in the lower tank of coupled tank systems 1 and 2, for self-triggered (ST) and periodic (P) strategies.

TABLE I
COMPARISON OF THE SELF-TRIGGERED AND PERIODIC IMPLEMENTATION FOR AN EXPERIMENT OF 320s.

	Periodic	Self-Triggered
Number of transmissions	427	62
Total current consumption	0.0496 mAh	0.0293 mAh
Battery life (2900mAh)	215.6 days	365.5 days

the water basin to the upper tank, which flows to the lower tank. The holes in each of the tanks have the same diameter. In order to introduce a disturbance in this system, the first tank has a drain tap such that, when opened, the liquid can flow directly to the water basin.

The first experiment consists of a command to raise the water level to 10cm. Fig 3 shows that both strategies, periodic and self-triggered, provide matching performances, even if the message exchange under the self-triggered approach is considerably lower, as shown in Table I. Table I also depicts the total current consumption of the wireless sensor nodes. Even though the number of transmissions of the self-triggered control scheme is only 14.5% of the periodic, the battery lifetime increase is 41% and not 85.5% as it could be expected. This difference comes from the fact that certain non-control related message exchange is imposed by the protocol, and therefore a reduction in the number of transmissions does not imply the same amount of energy savings. Not only self-triggered requires less energy but also it demands less bandwidth, that is thus available for the other nodes present in the network.

In order to confirm the robustness of the self-triggered strategy, experiments for level disturbance were also considered. As before, we observed similar behaviors under the periodic and the self-triggered strategy. The latter adjusts the transmission times according to the state of the plant (not displayed here due to space constraints). These set of experiments reveal that this paradigm appears to be an efficient solution -in terms of energy and bandwidth- for wireless control systems.

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