Automatica 91 (2018) 1–9

Contents lists available at ScienceDirect

Automatica

journal homepage: www.elsevier.com/locate/automatica

Random access design for wireless control systems☆

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ARTICLE INFO

Article history:
Received 21 April 2016
Received in revised form 3 June 2017
Accepted 17 December 2017

Keywords:
Networked control systems
Random access
Optimization
Decentralized systems
Communication channels

ABSTRACT

Interferences arising between wireless sensor–actuator systems communicating over shared wireless channels impact closed loop control performance. We design interference-aware channel access policies where the total transmit power of the sensors is minimized while desired control performance is guaranteed for each involved control loop. Control performance is abstracted as an expected decrease rate of a Lyapunov function for each loop. We prove that the optimal channel access policies are decoupled so that, intuitively, each sensor balances the gains from transmitting to its actuator with the negative interference effect on all other control loops. Moreover the optimal policies are of a threshold nature with respect to channel conditions, that is, a sensor transmits only under favorable local fading conditions. Finally, the optimal policies can be computed by a distributed iterative procedure which does not require coordination between the sensors.

1. Introduction

Wireless sensors are an essential part of modern smart communities where they are deployed to monitor and control physical processes in our homes, urban infrastructures, agriculture, and industrial plants. This abundance of wireless devices however also creates an increase in the wireless interferences arising between transmissions over the shared wireless medium. The development of decentralized communication mechanisms that can manage these interference effects and guarantee closed loop control performance arises as an important research direction.

The prevalent approach to the problem of sharing a wireless communication medium in networked control systems is centralized scheduling which guarantees no interferences. Static scheduling for example specifies that sensors transmit in some predefined periodically repeating sequence such as round-robin and this sequence is designed to meet control objectives, see, e.g., Hristu-Varsakelis (2001), Le Ny, Feron, and Pappas (2011) and Zhang, Branicky, and Phillips (2001). Deriving optimal scheduling sequences is recognized as a hard combinatorial problem (Gupta, Chung, Hassibi, & Murray, 2006; Rehbinder & Sanfridson, 2004). Scheduling can also be dynamic, where at each time step a central network coordination authority decides which device gets access to the medium. This dynamic decision may be stochastic (Gupta et al., 2006), based on plant state information (Donkers, Heemels, Van De Wouw, & Hetel, 2011; Walsh, Ye, & Bushnell, 2002), or based on the wireless channel conditions (Gatsis, Pajic, Ribeiro, & Pappas, 2015).

Besides scheduling, decentralized mechanisms where sensors independently decide access to the shared wireless medium also become practically useful for sensors that communicate information infrequently. Compared to centralized approaches they are easier to implement as they do not require predesigned sequences of how sensors access the medium, or a central authority to take scheduling decisions. The drawback of this decentralized approach however is that packet collisions can occur from simultaneously transmitting sensors, resulting in lost packets and control performance degradation. Hence sensor access policies need to be appropriately designed taking into account these effects. We consider specifically a random access mechanism where each sensor independently and randomly decides whether to transmit plant state measurements over a shared channel to an access point/controller (Fig. 1).

Control under random access communication mechanisms has drawn limited attention, to the best of our knowledge. Comparisons between different medium access mechanisms for networked control systems and the impact of packet collisions in stability and control performance have been considered either in numerical simulations (Liu & Goldsmith, 2004; Ramesh, Sandberg, & Johansson, 2013) or analytically in simple cases (Blind & Allgöwer, 2011; Rabi, Stabellini, Proutiere, & Johansson, 2010).

☆ This work was supported in part by NSF CNS-0931239, and by TerraSwarm, one of six centers of STARnet, a Semiconductor Research Corporation program sponsored by MARCO and DARPA. The material in this paper was partially presented at the 54th IEEE Conference on Decision and Control, December 15-18, 2015, Osaka, Japan. This paper was recommended for publication in revised form by Associate Editor Claudio De Persis under the direction of Editor Christos G. Cassandras.

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https://doi.org/10.1016/j.automatica.2018.01.021

These include random access mechanisms and related Aloha-like schemes, where after a packet collision the involved sensors wait for a random time interval and retransmit. Stability conditions under packet collisions were examined in Tabbara and Nesic (2008) and Zhang (2003). In contrast to these works, our goal is to directly design the medium access mechanism to guarantee control performance. Besides closed loop control, optimal remote estimation over collision channels is considered recently in Vasconcelos and Martins (2017).

We pose the design of channel access policies for multiple control loops over a shared wireless channel as an optimization problem (Section 2). The goal is to satisfy a control performance requirement for each control loop while minimizing the total expected transmit power expenditures. We adopt a Lyapunov-like control performance abstraction, motivated from our work on centralized scheduling (Gatsis, Pajic, et al., 2015). Each control system is abstracted via a given Lyapunov function which is required to decrease at a desired rate and in expectation over to the random packet losses and collisions on the shared medium.

Besides accounting for packet collisions, sensors can exploit channel fading state information. Fading refers to large unpredictable variations in wireless channel transferences (Goldsmith, 2005, Ch. 3,4), affecting the likelihood of successful packet decoding. This communication model has been used in estimation and control applications (Gatsis, Pajic, et al., 2015; Gatsis, Ribeiro, & Pappas, 2014; Quevedo, Ahlén, Leong, & Dey, 2012) but not under a random access mechanism. By adapting online to channel states sensors may, e.g., access the channel at higher rates under channel conditions with higher packet success. In preliminary work presented in Gatsis, Ribeiro, and Pappas (2015) we considered this random access problem but employing simpler policies that do not adapt to channel states online.

Based on Lagrange duality arguments we characterize the structure of the optimal sensor access policies (Section 4). We show that the optimal policies are of a threshold nature, that is, each sensor transmits only when its corresponding channel state is favorable enough and backs off otherwise. Moreover we reveal an intuitive decoupling among sensors; each sensor should select its threshold in a way that balances the control performance of its own closed loop with the collective negative effect it has on all other control loops due to collisions. Optimal decentralized policies are also known for general wireless random access networks targeting throughput (Adireddy & Tong, 2005; Hu & Ribeiro, 2011; Qin & Berry, 2006), but this is the first time this is shown for control performance.

In Section 5 we derive an iterative procedure to compute the optimal access policies. The procedure is easy to implement in our architecture as it does not require the sensors to coordinate among themselves, or to know what control performance the other sensors try to achieve. We conclude with a numerical example and some remarks (Sections 6, 7).

2. System description

We consider a wireless control architecture where m independent plants are controlled over a shared wireless medium. Each sensor i ($i = 1, 2, \dots, m$) transmits measurements of plant i to an access point responsible for computing the plant control inputs. Packet collisions might arise on the shared medium between simultaneously transmitting sensors. See Fig. 1 for an illustration. We are interested in designing a mechanism for each sensor to independently decide whether to access the medium (random access) in a way that guarantees desirable control performance for all control systems.

The dynamics for each of the m control systems are assumed pre-designed independently of the communication policy, and are described by a switched model that depends on whether the controller manages to reach the access point or not. Thus, if we use $\gamma_{i,k} \in \{0, 1\}$ to indicate the success of the transmission at time k for link/system i and assume the system is linear and time invariant, we can model its evolution by the switched system

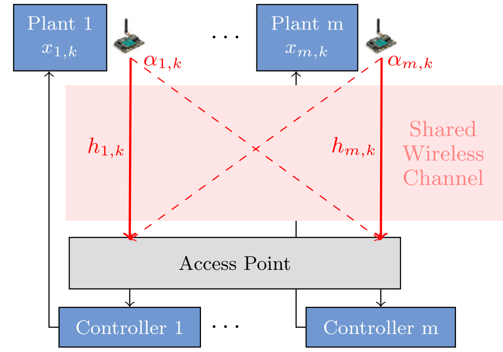

Fig. 1. Random access architecture for m control loops over a shared wireless medium. Each sensor i randomly transmits with probability $\alpha_{i,k}$ at time k to a common access point computing the plant control inputs. If only sensor i transmits, the successful decoding probability depends on local channel conditions $h_{i,k}$. If other sensors transmit at the same time a collision might occur at sensor i's transmission, rendering i's packet lost.

$$x_{i,k+1} = \begin{cases} A_{c,i}\, x_{i,k} + w_{i,k}, & \text{if } \gamma_{i,k} = 1, \\ A_{o,i}\, x_{i,k} + w_{i,k}, & \text{if } \gamma_{i,k} = 0. \end{cases} \tag{1}$$

Here $x_{i,k} \in \mathbb{R}^{n_i}$ denotes the state of control system i at each time k, which can in general include both plant and controller states — see, e.g., Example 1. At a successful transmission the system dynamics are described by the matrix $A_{c,i} \in \mathbb{R}^{n_i \times n_i}$, where 'c' stands for closed-loop, and otherwise by $A_{o,i} \in \mathbb{R}^{n_i \times n_i}$, where 'o' stands for open-loop. We assume that $A_{c,i}$ is asymptotically stable, implying that if system i successfully transmits at each slot the state evolution of $x_{i,k}$ is stable. The open loop matrix $A_{o,i}$ may be unstable. The additive terms $w_{i,k}$ model an independent (both across time k for each system i, and across systems) identically distributed (i.i.d.) noise process with mean zero and covariance $W_i \succeq 0$.

Example 1. Suppose each closed loop i consists of a linear plant and a linear output of the form

$$x_{i,k+1} = A_i x_{i,k} + B_i u_{i,k} + w_{i,k}, \tag{2}$$

$$y_{i,k} = C_i x_{i,k} + v_{i,k}, \tag{3}$$

where $\{w_{i,k},\ k \geq 0\}$ and $\{v_{i,k},\ k \geq 0\}$ are i.i.d. Gaussian disturbance and measurement noises respectively. Each wireless sensor i transmits the output measurement $y_{i,k}$ to the controller. A dynamic control law adapted to the packet drops keeps a local controller state $z_{i,k}$,

$$z_{i,k+1} = F_i\, z_{i,k} + \gamma_{i,k}\,(F_{c,i}\, z_{i,k} + G_i\, y_{i,k}) \tag{4}$$

which may for example represent a local estimate of the plant state (Hespanha, Naghshtabrizi, & Xu, 2007), and applies plant input $u_{i,k}$ as

$$u_{i,k} = K_i\, z_{i,k} + \gamma_{i,k}\,(K_{c,i}\, z_{i,k} + L_i\, y_{i,k}). \tag{5}$$

In other words, the controller updates appropriately the local state and input whenever a measurement is received. The overall closed loop system is obtained by joining plant and controller states into

$$\begin{bmatrix} x_{i,k+1} \\ z_{i,k+1} \end{bmatrix} = \begin{bmatrix} A_i + \gamma_{i,k} B_i L_i C_i & B_i K_i + \gamma_{i,k} B_i K_{c,i} \\ \gamma_{i,k} G_i C_i & F_i + \gamma_{i,k} F_{c,i} \end{bmatrix} \cdot \begin{bmatrix} x_{i,k} \\ z_{i,k} \end{bmatrix} + \begin{bmatrix} I & \gamma_{i,k} B_i L_i C_i \\ 0 & \gamma_{i,k} G_i \end{bmatrix} \begin{bmatrix} w_{i,k} \\ v_{i,k} \end{bmatrix} \tag{6}$$

which is of the form (1). □