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Hybrid event-time-triggered networked control systems: Scheduling-event-control co-design

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ABSTRACT

This paper is concerned with the simultaneous stabilization of a collection of plants remotely controlled via a wireless network. The so-called most regular binary sequences (MRBSs) are used to allocate the limited network channels. To further reduce unnecessary transmissions, an event-triggered transmitter is introduced at each plant. Under the hybrid event-time-triggered transmission strategy, a sufficient stability condition is derived for each plant. Then, a unified co-design framework is presented with which the scheduling functions (i.e., the MRBSs), the event-triggering condition and the controller gains can be determined simultaneously. The main results are established using piecewise Lyapunov functional method and average dwell time technique. The effectiveness of the co-design method is demonstrated by a numerical example.

1. Introduction

In wireless networked systems (such as wireless sensor networks) consisting of a large number of nodes, network capacity limitation is often a serious issue. Capacity limitation, also known as medium access constraint, means that at any time only a limited number of nodes can simultaneously access to the network. It is frequently seen in many applications, e.g., vehicular networks, intelligent transportation systems, power systems, sensor networks for environment monitoring. To deal with medium access constraint, an effective scheduling policy (referred to as communication protocol) is of great importance for stability and performance requirement. There are in general two types of scheduling protocols widely in use: static protocols and dynamic protocols. With a static protocol, network transmission is assigned to the nodes periodically in a predefined order [14,27]. One of the simplest static protocols is the round-robin (RR), which assigns the network transmission to each node in equal portions and in circular order, handling all the nodes without priority. In a dynamic protocol, e.g., try-once-discard (TOD), the assignment of network transmission depends on system states. For example, the network access can be enabled to the node with the largest discrepancy between the current and the latest transmitted state [19,24]. As dynamic scheduling uses the idea of state feedback, it is also known as feedback scheduling.

Traditionally, both static and dynamic scheduling methods operate on a time basis, and hence, they are called as time-triggered scheduling. Albeit very convenient for design and useful in most cases, time-triggered scheduling might be inefficient in some situations for resource allocation and energy cost minimization [5]. For instance, when a control system runs in a steady state and the output variance is negligible, updating the measurement and control input is clearly unnecessary.

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Using a time-triggered strategy in such a situation apparently may result in a waste of the network resource. Motivated by this fact, event-triggered scheduling has attracted considerable research attention recently. In an event-triggered scheme, a task is executed after the occurrence of a certain event, rather than after the elapse of a period of time. The event is generated by a well-designed event-triggering mechanism [16]. Being clock-free and less demanding for transmission, event-triggered control is capable of improving the network resource utilization while retaining a satisfactory control performance [6]. A detailed comparison between time-triggered and event-triggered schemes can be seen in [1] (called Riemann sampling and Lebesgue sampling, respectively). Recently, various event-triggering mechanisms (either dependent on or independent of the plant state) have been proposed, such as send-on-delta scheme [18], level-crossing scheme [3], send-on-area scheme [20], self-triggered scheme [2].

Here, we are interested in a hybrid *time-event-triggered* control problem, i.e., some of the system components are time-triggered while others are event-triggered. Such a problem may arise in situations where a collection of plants are controlled by a remote controller via a wireless network whose capacity is limited. The plants may be scheduled to have access to the network in a time-triggered manner, while the transmission of the sensor data at each plant might be triggered by an event in the environment. Obviously, extending a purely time-triggered or event-triggered scheme to a hybrid time-event triggered transmission case is not feasible. Due to capacity limitation, the network scheduler should guarantee that, at any time, a given number of plants have access to the network and close its feedback control loop while the remainder plants run without updating their control inputs. On the other hand, the event-triggered transmitters should be designed to avoid unnecessary transmission between the plants and the remote controller, i.e., measurement with negligible variation will not be transmitted when network transmission is authorized by the network scheduler.

For NCSs with medium access constraint and hybrid time-event-triggered transmission mechanism, the design procedure involves designing an effective time-triggered scheduling sequence for the time-triggered components and establishing an event-triggering strategy for the event-triggered components. Also, one needs to design a set of feedback controllers to stabilize the collection of subsystems simultaneously. As the three aspects are strongly coupled, the scheduling-event-controller joint design problem is rather challenging. Recently, a scheduling-controller co-design strategy with a static communication protocol was presented in [27]. The results were extended to linear quadratic Gaussian (LQG) control problem in [14]. Similar scheduling-controller co-design problems with dynamic communication protocols were studied in [7,10–12]. For instance, [7] suggested a scheduling-controller co-design algorithm for a dynamic output feedback controller and a TOD protocol dependent on the network induced state errors. Lately, scheduling-controller co-design issue was also investigated in the context of simultaneous stabilization of a collection of plants via limited shared communication channels, see [8,15], where a time-division scheduling and control co-design method is proposed that based on average dwell time technique and Lyapunov method [17,25,26]. To date, the problem of scheduling-event-controller co-design has not been investigated.

This paper investigates NCSs with a large number of plants under control of a remote controller via wireless communication networks with limited channels. The control signal of each plant is computed by the remote controller and sent to a relay station responsible for the plant. To handle medium access limitation, we use at each relay station a special type of communication protocols defined by a most regular binary sequence (MRBS, see, [4]) to govern its network access. The protocol sequences are designed to split the transmission slots so that all the plants are accommodated on demand. This is realized by yielding a series of ones and zeros which are non-uniformly distributed with a constant average rate in a cycle. Therefore, for any plant with a request data rate, the protocol can allocate transmission slot to it with an asymptotic rate equal to what is requested. At each plant, the transmission of measurement is governed by an event-triggered transmitter located at the sensor so that the sampled data is sent to the remote controller only if an event condition is satisfied. With the MRBS sequence and the event-triggering mechanism, transmission happens between a plant and the remote controller if and only if an event is triggered while the scheduler is assigning network access to the plant. The difficulty of the hybrid scheduling-event-controller co-design lies in constructing a time-triggered scheduling function and an event-triggered transmission scheme in one framework and designing them along with the controller. Our main contributions lie in establishing the relationship between the MRBS protocol sequences at the relays, the event-triggering mechanisms and stability and performance of the plants. Most importantly, we develop a co-design approach to the event-triggering mechanism, the state feedback controller and the MRBS protocol, which is defined by a so-called generating function. In particular, we give a unified framework with which the parameters in the generating function of the MRBS protocol, the event-triggering condition and the feedback gains of the controllers can be determined simultaneously.

Notation. The notation used throughout the paper is fairly standard. The superscript 'T' stands for matrix transposition; R^n denotes the n-dimensional Euclidean space and notation $P > 0$ ($\geqslant 0$) means that P is real symmetric and positive definite (semi-definite). In symmetric block matrices, we use an asterisk ($*$) to represent a term that is induced by symmetry. Matrices, if their dimensions are not explicitly stated, are assumed to be compatible for algebraic operations.

2. Problem formulation

In this paper, we consider an NCS containing N plants coordinated by a remote controller (see in Fig. 1) via a wireless communication network. The computer system plays the role of the remote controller, which calculates the control input