Control Engineering Practice 26 (2014) 72–81

Contents lists available at ScienceDirect

Control Engineering Practice

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

Bandwidth allocation and scheduling of networked control systems with exponential and quadratic approximations

Jiawei Dong*, Won-Jong Kim

Department of Mechanical Engineering, Texas A&M University, College Station, TX, USA

ARTICLE INFO

Article history:
Received 6 November 2012
Accepted 2 January 2014
Available online 6 February 2014

Keywords:
Networked control system
Bandwidth allocation
Scheduling
Exponential approximation
Quadratic approximation

ABSTRACT

This paper investigates bandwidth allocation and scheduling of networked control systems (NCSs) with nonlinear-programming techniques. The bandwidth utilization (BU) is defined in terms of sampling frequency. An exponential and a quadratic approximation are formulated to describe system performance versus the sampling frequencies. The optimal sampling frequencies are obtained by solving the approximations with Karush–Kuhn–Tucker (KKT) conditions. Experimental results verify the effectiveness of the proposed approximations and scheduling algorithms. The two approximations could find an optimal BU of an NCS with a given sequence of plants and maximize the total BU up to 98% of the total available bandwidth.

1. Introduction

Networked control systems attract significant attentions recently due to their advantages of easy maintenance, architecture flexibility, reduced wiring cost, etc. However, the design of an NCS requires not only participation of controller designers but also real-time operating-system (RTOS) designers because of the introduction of the networks. Traditionally, a controller design problem is separate from software design and implementation. This separation allows controller designers to disregard the characteristics of the computational and communication resources, but mainly focus on the stability and performance of the controllers and the systems. On the other hand, the RTOS designers consider the control loops as periodic tasks with hard deadlines and focus more on how to schedule all the tasks and guarantee that the tasks do not miss their deadlines (Arzen, Cervin, Eker, & Sha, 2000). In the NCSs, however, these two fields are correlated in a closer way so that their separation will lead to poor system performances. The ideal linear relation between the system performance and the sampling frequency is no longer the case for the NCS design because of the existence of the network.

A representative framework of an NCS is shown in Fig. 1. In this framework, the NCS includes several operation scenarios—(i) a single controller controls a single plant, (ii) a single controller controls multiple plants, and (iii) multiple controllers collaboratively control a single plant, etc. In this framework, all the controllers and the plants will compete for the limited resources, such as the central processing unit (CPU) time, network bandwidth, and battery, in the NCS to maintain the stability and performance. More often, one could expect the global information sharing and resource allocation could dynamically adjust the performance of each plant so that the entire NCS could be maintained at a desirable level. Therefore, the communicational and computational resource allocation and scheduling plays a crucial role in the design of an NCS.

Traditionally, digital control ideally assumes that the system performance index can be reflected by a monotonically decreasing linear or exponential function of the sampling frequency. In other words, a higher sampling frequency yields better performance. In practice, this is not always the case as noise, numerical errors, and hardware limits exist in reality. NCS is one of the exceptions because networks have bottlenecks as hardware limits such that the ideal monotonic linear performance function no longer holds for the design of an NCS (Lian, 2001). A higher sampling frequency will increase the number of data packets in the network, which will cause longer time delays and might even overload and destabilize the network. Therefore, the linear models of the system performance proposed in the aforementioned literature could not completely represent the system dynamics in an NCS. The effects on the system performance with possibly longer time delays brought by a high sampling frequency should be considered when formulating the performance index function (PIF) of an NCS. Fig. 2 gives intuitive trends of the system performance of an NCS with respect to the sampling frequency. In Fig. 2, f_γ is the optimal sampling frequency that yields the optimal system performance of an NCS. Sampling frequencies f_α and f_β are the boundaries of the acceptable performance range.

* Corresponding author. Tel.: +1 979 842 2649.
E-mail address: jwdong@aggienetwork.com (J. Dong).

0967-0661/$ - see front matter
http://dx.doi.org/10.1016/j.conengprac.2014.01.001

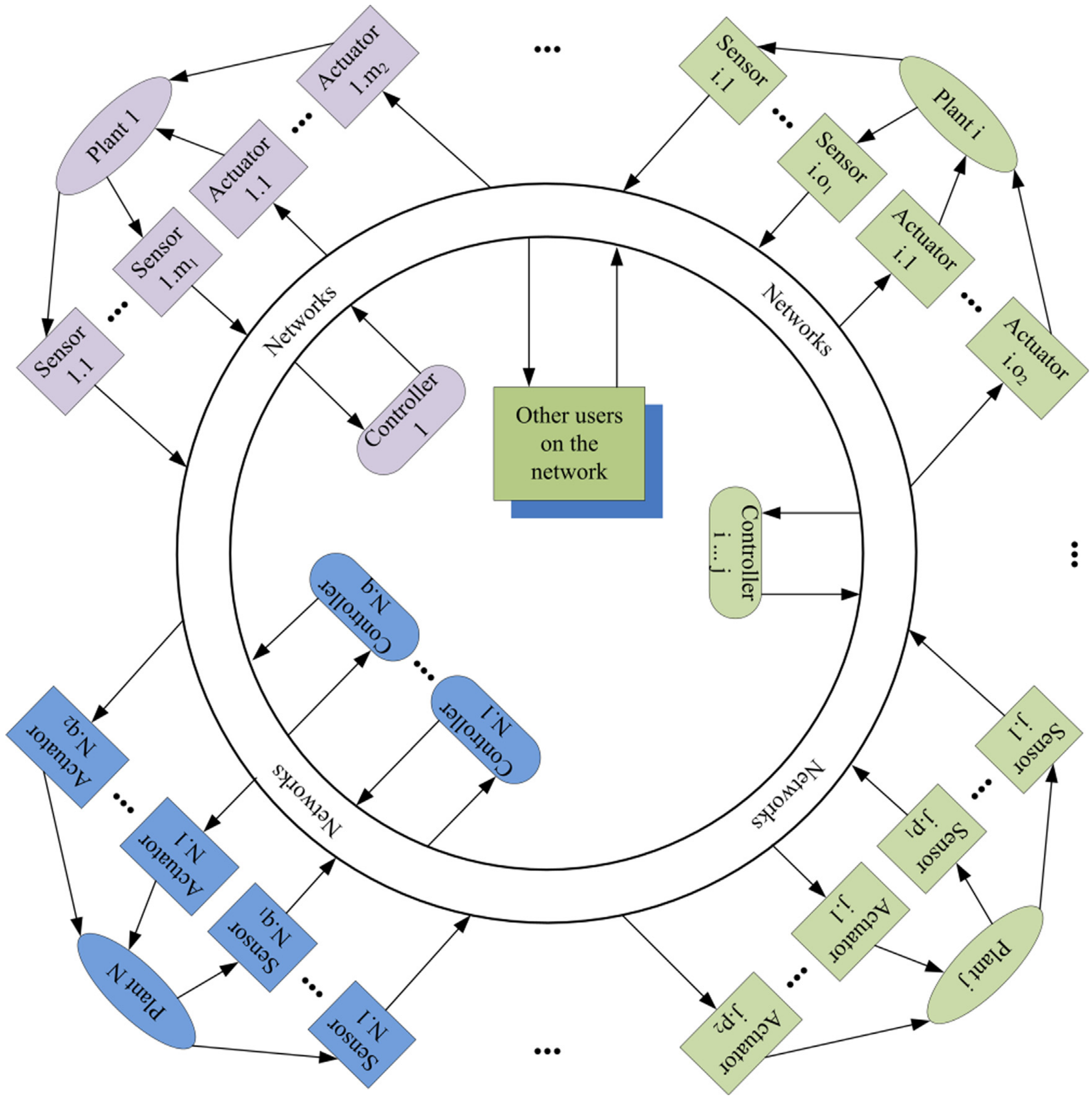

Fig. 1. A representative framework of an NCS.

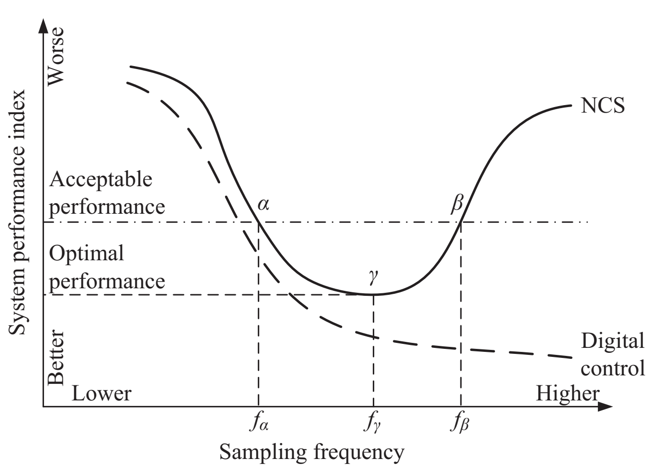

Fig. 2. Performance index versus sampling frequency (Lian, 2001).

Several research projects have been conducted in this area. Zhang, Gao, and Kaynak (2013) gave a research survey of network-induced constraints of the NCS including time delays, packet losses, resource competition, data quantization, etc. The resource competition should be solved from the control perspective to equip the NCS with calculating optimal sampling frequencies and a dynamic scheduler based on Zhang's survey. The convex optimization applied in the paper is one of the most powerful and popular tools that could solve the resource-allocation issue effectively. A dynamic bandwidth allocation algorithm based on captured visual content information was presented to raise the BU of an NCS (Lin & Lian, 2012). The algorithm was to evenly distribute resources to each node in the NCS and then dynamically revise their allocation based on a linear performance evaluation whereas our proposed methods dynamically reschedule each client based on their performance changing rate with respect to the sampling frequency. A network bandwidth allocation with time reservations was studied (Belzarena, Ferragut, & Paganini, 2009). The NCS involved fully distributed solutions over an arbitrary network topology in terms of revenue that was computed via distributed convex optimization. Effects of the sampling period to an NCS were discussed, and an optimized model and optimal sampling period selection algorithm was proposed based on the control performance optimization and network scheduling condition (Wang & Liu, 2011). A bandwidth-allocation scheme formulated as a convex optimization problem for NCSs was proposed (Al-Hammouri, Branicky, Liberatore, & Phillips, 2006). A co-design approach was proposed to treat