Automatica 50 (2014) 1875–1883

Contents lists available at ScienceDirect

Automatica

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

Brief paper

Markovian jump guaranteed cost congestion control strategies for large scale mobile networks with differentiated services traffic[☆]

Rui Ru Chen, Khashayar Khorasani [1]

Department of Electrical and Computer Engineering, Concordia University, Montréal, Québec, Canada, H3G 1M8

A R T I C L E I N F O

Article history:
Received 1 May 2013
Received in revised form
10 March 2014
Accepted 29 March 2014
Available online 27 May 2014

Keywords:
Congestion control
Guaranteed cost control
Markovian jump systems
Large scale networks
Differentiated services traffic
Time-delay systems

A B S T R A C T

In this paper, two novel congestion control strategies for mobile networks with differentiated services (Diff-Serv) traffic are presented, namely (i) a Markovian jump *decentralized* guaranteed cost congestion control strategy, and (ii) a Markovian jump *distributed* guaranteed cost congestion control strategy. The switchings or changes in the network topology are modeled by a Markovian jump process. By utilizing *guaranteed cost control* principles, the proposed congestion control schemes do indeed take into account the associated physical network resource constraints and are shown to be robust to *unknown* and *time-varying* network latencies and time delays. A set of Linear Matrix Inequality (LMI) conditions are obtained to guarantee the QoS of the Diff-Serv traffic with a guaranteed upper bound cost. Simulation results are presented to illustrate the effectiveness and capabilities of our proposed strategies. Comparisons with *centralized* and other relevant works in the literature focused on Diff-Serv traffic and mobile networks are also provided to demonstrate the advantages of our proposed solutions.

1. Introduction

With the increasing demand of multimedia applications, differentiated services have been considered in many applications of communication networks. Specifically, the Internet Engineering Task Force (IETF) has proposed the Differentiated Services (Diff-Serv) architecture (Chan, Babiarz, & Baker, 2008; Pitsillides, Ioannou, Lestas, & Rossides, 2005a; Tipper, Qian, & Hou, 2004) to deliver aggregated quality of service (QoS) in IP networks. In the Diff-Serv architecture the traffic is aggregated into different classes of flows and the bandwidth allocation and the packet dropping rules are applied to the traffic classes according to their QoS requirements and specifications.

For the TCP/IP networks, a number of congestion control design techniques have been proposed in the literature. However, the standard and existing TCP based congestion control mechanisms cannot adequately address simultaneously the congestion problem and achieve fairness among traffic aggregates corresponding to the Diff-Serv networks (Floyd & Jacobson, 1993; Lee, John, & John, 2006). It has been recognized that generally scaling up the existing congestion control approaches that use *ad hoc* and intuitive techniques are not formal in nature and are indeed of limited use even with a number of proposed tuning solutions. Furthermore, by merely relying on the TCP congestion control algorithms, the QoS requirements expected from the Diff-Serv traffic cannot be fully realized (Lee, Ng, & Asanovic, 2012).

Several new congestion control schemes for Diff-Serv networks whose performance can be analytically established have been presented in the literature by using for example sliding mode control (Bouyoucef & Khorasani, 2009), robust adaptive control (Pitsillides et al., 2005a; Pitsillides, Ioannou, Lestas, & Rossides, 2005b) switching control (Chen & Khorasani, 2010, 2011b), and other methodologies (Curtis, Pasiliao, Shea, & Dixon, 2012; Ignaciuk & Bartoszewicz, 2013; Wojcik & Jajszczyk, 2012; Yaghmaee & Adjeroh, 2009), and (Nichols & Van Jacobson, 2012). Other nonlinear time delay systems have also been used for congestion control. In such systems, stability and bifurcation phenomena have both been exhibited in the models and in simulations (Han, Hollot, Towsley, & Chait, 2005) and (Raina, Towsley, & Wischik, 2005).

The approaches proposed in Pitsillides et al. (2005a,b); Tipper et al. (2004) are designed for *only* a *cascade network* and the unknown and time-varying delays are *not* considered in the design of the congestion control scheme. The lack of explicit consideration for the prevailing delay phenomena can result in fundamental challenges in guaranteeing network performance, and can even

---

[☆] The material in this paper was not presented at any conference. This paper was recommended for publication in revised form by Associate Editor Abdelhamid Tayebi under the direction of Editor Toshiharu Sugie.

E-mail addresses: chenruiru@hotmail.com (R.R. Chen), kash@ece.concordia.ca (K. Khorasani).

[1] Tel.: +1 514 848 2424x3086; fax: +1 514 848 2802.

http://dx.doi.org/10.1016/j.automatica.2014.05.004
0005-1098/© 2014 Elsevier Ltd. All rights reserved.

cause an instability when these approaches are applied to large scale networks consisting of many nodes structured in *arbitrary configurations* containing feedback as reported in our earlier works in Bouyoucef and Khorasani (2009); Chen and Khorasani (2010, 2011b). On the other hand, the approaches proposed in our preliminary development of the results that are reported in this paper in Chen and Khorasani (2010, 2011b) need to regulate the traffic compression gains among the network nodes to guarantee stability. However, in certain cases this regulation may lead to conservative results and low quality of service. This is one of the main motivations for the development of our methodology in this work for relaxing and generalizing the conditions obtained in our earlier works in Chen and Khorasani (2010, 2011a,b). There are a number of other related work and approaches on queuing management. Active queue management can also yield QoS metrics, such as low latency. One of the simplest commonly used queuing policies is Drop-Tail (Comer, 2005). Further investigation and analysis of these policies will be a topic that will be studied as part of our future work.

The main objective of this paper is to improve and generalize the performance of the so-called "*switching congestion control*" (SCC) approach that we have developed recently in Chen and Khorasani (2010) and (Chen & Khorasani, 2011b) through utilization of the *guaranteed cost control (GCC)* approach (Boukas, Liu, & Al-Sunni, 2003). A preliminary version of our results has appeared recently in Chen and Khorasani (2011a). It should also be noted that the results in Chen and Khorasani (2011b) are applicable to **only fixed topology** networks, whereas the results in the present work are developed and generalized to **switching** and **mobile** large scale networks. This is of the main contributions and extensions of our work as compared to those that we have already reported in Chen and Khorasani (2010, 2011a,b).

The changes and switchings in the network topologies are modeled by a Markov chain and the dynamics of the mobile network are represented by a nonlinear time-delay system with Markovian jump parameters. A guaranteed cost control approach is then developed, and for the *first time in the literature* utilized for synthesis and design of congestion control strategies for the Diff-Serv traffic in mobile networks.

The main contributions of this paper can be summarized as:

(1) A novel *decentralized* Markovian jump guaranteed cost control (MJ-GCC) strategy for mobile Diff-Serv networks is developed. By utilizing the GCC approach, the congestion controller for a node incorporates information from *only* the nearest neighboring nodes and can first be developed *without* considering the network physical constraints unlike our earlier work in Chen and Khorasani (2010). Therefore, our first contribution is the generalization of the results reported in Chen and Khorasani (2010).

(2) A formal robust stability of the closed-loop system is provided by satisfying a set of linear matrix inequality (LMI) conditions that incorporates the physical constraints of the problem.

(3) Through simulations we have demonstrated that significant QoS performance improvements can be achieved when compared to the existing approaches in the literature (Chen & Khorasani, 2010; Pitsillides et al., 2005a,b) (refer to the results summarized in Tables 1 and 2).

(4) A novel *distributed* Markovian jump guaranteed cost control (MJ-GCC) strategy for mobile Diff-Serv networks is proposed for the *first time in the literature* (note that this approach has NOT been reported even in our previous works).

(5) The proposed methodology incorporates information from *only* the nearest neighboring nodes states *in addition* to communication *among* only the nearest neighboring *controllers* for designing the distributed control strategy.

(6) Our proposed distributed congestion control approach is shown through simulations to yield an improvement over the performance of the decentralized control approach as reported in this work as well as our earlier work in Chen and Khorasani (2011a) (refer to the results summarized in Tables 3 and 4).

(7) Our proposed distributed MJ-GCC approach is also evaluated and compared with the decentralized MJ-GCC approach developed in this work as well as presented in its preliminary form in Chen and Khorasani (2011a) with respect to the QoS performance and control efforts characteristics to demonstrate the superiority of the distributed approach over the decentralized scheme.

The organization of this paper is as follows. In Section 2, dynamical model of the Markovian jump process of the mobile networks subject to the Diff-Serv traffic is presented. In Section 3, our novel *decentralized* guaranteed cost congestion control strategy is proposed. In Section 4, our novel *distributed* guaranteed cost congestion control strategy is presented. The stability conditions of these control strategies incorporating all the physical constraints are derived in Section 5. Simulations results and comparative studies between the decentralized and the distributed congestion control methodologies as well as relevant centralized and other approaches in the literature that demonstrate and illustrate the advantages and superiority of our proposed methodologies are presented in Section 6 and the conclusions are stated in Section 7.

2. Problem formulation

2.1. Fluid flow model of mobile networks

In this paper, we assume that the dynamics of a queue is governed by an M/M/1, since the resulting queuing system can be applied to describe a wide variety of queuing models as found in systems with a very large number of independent customers/nodes that can be approximated by a Poisson process. Given an M/M/1 queue the dynamics of the ith node can be expressed by a fluid flow model as follows (Filipiak, 1988; Pitsillides et al., 2005b)

$$\dot{x}_i(t) = -\mu_i \frac{x_i(t)}{1 + x_i(t)} C_i(t) + \lambda_i(t) \tag{1}$$

where $x_i(t)$ is the queuing length, $C_i(t)$ is the link capacity, $\lambda_i(t)$ is the average rate of incoming traffic, and $1/\mu_i$ is the average length of the packets being transmitted.

Consider a large scale mobile network with n nodes. In this work, the nodes can be assigned as belonging to different *clusters* according to their connections. Within each *cluster*, all the nodes can communicate with each other and can be fully connected. However, among different *clusters*, only selected nodes (e.g. the decision making or gateway nodes) can communicate with other clusters. Therefore, the input traffic to each node can consist of two parts, namely: (1) the external traffic $\lambda_i(t)$ which in principle could represent the traffic that is being sent from nodes of other clusters (specifically defined as groups of nodes not belonging to the nearest neighboring set $\wp_i$ of node i) as well as disturbances or environmental stimuli, and (2) the internal traffic $\lambda_j(t - \tau_{ji}(t))$ which is the delayed input traffic from all the neighboring nodes within a given cluster (cf. Fig. 2 on page 11).

Furthermore, due to the nodes' mobility the neighboring set of each node is dependent on the network topology (or its mode). Therefore, by using the representation (1) the fluid flow model corresponding to each node $i = 1, \ldots, n$ in a mobile network is governed by

$$\dot{x}_i(t) = -f(x_i(t))C_i(t) + \lambda_i(t) + \sum_{j \in \wp_i(\alpha_t)} \lambda_j(t - \tau_{ji}(t))g_{ji} \tag{2}$$

$$\lambda_j(t - \tau_{ji}(t)) = f(x_j(t - \tau_{ji}(t)))C_j(t - \tau_{ji}(t)) \tag{3}$$