Hybrid Modeling of Communication Networks Using Modelica

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I. Introduction

The objective with research on control of networks is often to improve traffic throughput and to better accommodate different service demands. Communication networks experience major problems due to traffic congestion. Today's congestion control is in most networks implemented as end-to-end protocols [7], [13], [12]. The protocols have proved to form the basis of a remarkably robust and scalable system, though the understanding of the basic principles of these complex systems are far from satisfactory [10], [11], [9].

The intention of this paper is to describe initial work on modeling packet-switched communication network using Modelica [1], [8], which is an object-oriented language for modeling physical systems. The standard modeling and simulation environment targeted at network research is the discrete-event simulator `ns-2` [2]. Since `ns-2` directly implements the Internet protocols and simulates individual packets, it provides on one hand accurate simulation results but on the other hand a rather slow simulation speed. The result of this is that `ns-2` is mainly for studying relatively small networks over a short time scale. The other extreme is to use flow models, i.e., to approximate packet transmission with a continuous flow and basically neglect the network protocols. A hybrid systems model, which is based on the average rates but takes packet drops and rate adjustments due to congestion control into account, was recently proposed in the literature [6]. The motivation for this model is to capture the network behavior on a time scale in between packet models and flow models. Studies have shown that the hybrid model is able to model many important network phenomena [6], [3]. In this paper, we show that the hybrid model is suitable for Modelica. Moreover, we show that the model can then be efficiently simulated using Dymola [5], which is one of the commercially available Modelica simulation environments.

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II. Hybrid Model

A hybrid system is a mathematical model for a dynamic system that has both continuous-time and discrete-event dynamics, e.g., [14], [4]. The traffic dynamics of a packet-switched communication network is suitable to model as a hybrid system, where the packet flows are approximated by continuous dynamics while packet drops and control protocols by discrete changes [6], [3]. For example, the queue state q models the number of packets stored in the buffer of a router and is updated through a continuous-time model. The model, however, depends on the discrete state of the queue: the queue is either in the state `queue-full` or in the state `queue-not-full`. Similarly, for TCP, the sending rate r and window size w are conveniently modeled as continuous variables, while the various modes of TCP (such as `slow-start`, `congestion avoidance`, and `fast recovery`) represent discrete states. See [6], [3] for details.

The motivation for introducing a hybrid model for communication networks is that it captures the behavior of the system on a time scale in between conventional packet models and flow models. Thanks to the model abstraction of packets, the simulation time is typically not affected by the number of packets transmitted or the queue sizes. Still, the hybrid model shows enough detail to accurately model transmission protocols and packet drops.

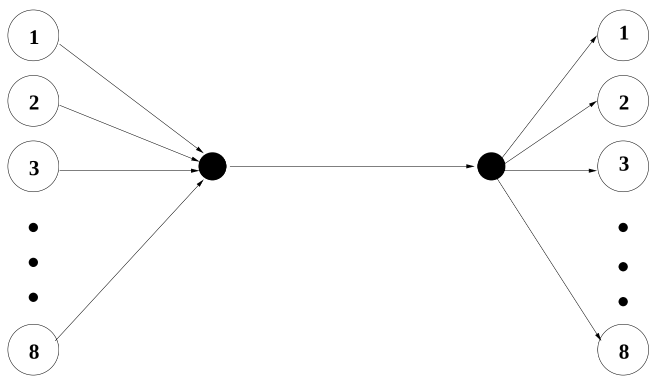

Fig. 1. Example of a bottleneck link with eight TCP flows.

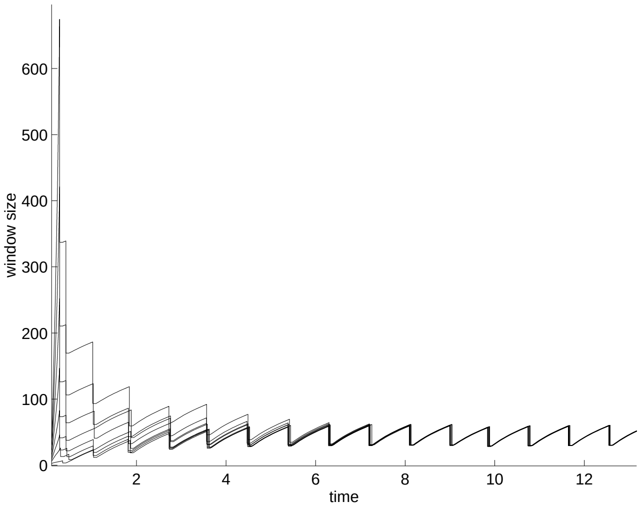

Fig. 2. Simulation results showing the congestion window sizes w_i for eight TCP flows. Note the characteristic sawtooth shaped signals and the synchronization, both due to the control strategy implemented by TCP.

III. Simulation Result

Let us illustrate the proposed model through an example, which illustrates synchronization of packet flows. It has been observed that the TCP window sizes tend to synchronize, see [15]. Consider the simple network in Figure 1, which consists of eight TCP flows and a single communication link. The network may represent a more complex network, which (during a certain time interval) has a specific bottleneck link limiting the throughput. Suppose the TCP flows have equal (and fixed) propagation time, which is determined by the physical length of the links and the speed of light. Figure 2 shows how the window sizes w_i, $i = 1, \dots, 8$, for the TCP flows synchronize after a short transient phase. Note that w_i converges to a periodic solution with a characteristic sawtooth shape, which is due to the additive increase multiplicative decrease (AIMD) control strategy of TCP [7].

IV. Discussion

Ongoing work includes the comparison of various TCP variants, such as TCP Reno, New Reno, SACK and Westwood, as well as the proposal of improved congestion control mechanisms. The modeling environment that we have developed based on Modelica provides a flexible modular platform for simulating various networks and protocols. Note, however, that the hybrid model is not only suitable for efficient simulation, but it is also possible to analyze the model using mathematical tools from hybrid systems theory. For example, the synchronization illustrated above has been theoretically justified in [6] using the hybrid model.

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