Real-time Performance Evaluation of Line Topology
Switched Ethernet

Fan Cen* Tao Xing Ke-Tong Wu
Institute of Acoustics, the Chinese Academy of Sciences, Beijing 100190, PRC

Abstract: Recently, switched Ethernet has become an active area of research because of its wide uses in industry. However, its uses have various real-time constraints on data communications. This paper analyzes the performance of the line topology switched Ethernet as a data acquisition network. Network calculus theory, which has been successfully applied to assess the real-time performance of packet-switched networks, is used to analyze the networks. To properly describe the activity of switches, a novel approach of modeling data flows into or out of switches is addressed. Based on our model, a concisely analytical expression of the maximal end-to-end delay in line topology switched Ethernet is derived. Finally, the relative simulation results are demonstrated. These results agree well with the analytical results, and thus they validate the data flow modeling techniques.

Keywords: Switched Ethernet, network calculus, end-to-end delay, line topology, real-time network.

1 Introduction

Industrial communications are currently based on several kinds of specific networks, namely fieldbus, such as CAN, Profibuses, and DeviceNet. They interconnect industrial devices in order to exchange data for the purpose of monitoring, controlling, and other industrial processes. A large number of these applications are time-constrained, and hence, the main purpose of a fieldbus is to ensure that the end-to-end delays of messages are bounded and remain limited compared with the time-constraints of an application. The fieldbus has solved many communication problems in industrial processes; however, there is no universally accepted standard that supports communication among different fieldbus networks. Limited bandwidth is another disadvantage of the fieldbus.

An existing and widely acceptable network technology has been found to be able to replace fieldbus; Ethernet is one of the most popular local area network (LAN) communication technologies. Several years ago, because of its random CSMA/CD bus arbitration, Ethernet could only be used for non-time-sensitive applications. At present, in most newly built Ethernets, the latest Ethernet switch technology is being used instead of the hub-based infrastructure. In other words, every device directly connects to a high-performance switch through a full duplex port such that every conflicting domain has only one device. In such point-to-point architectures, collisions cease to occur and the random back-off algorithm is no longer required. This provides an additional capability for Ethernet to support the transmission of time-critical information\(^\text{"1−7"}\). This aspect has received considerable attention for some time; current research mainly focuses on methods to determine the maximal delay of a network, in which field Network Calculus plays an important role\(^\text{"8−11"}\). Many researchers have attempted to develop a general model to represent switched ethernet; however, their models cannot obtain a concisely analytical result that shows the maximal delay, and the key factors impact the delay. A consensus has been reached that due to the diversity in industrial communications, it is difficult to determine whether or not Ethernet is real-time capable. It depends on the limit value set for the industrial application. To derive the maximal delay of a given network, complex models are constructed. A phenomenon, called pay burst only once, is known to offer a closer upper bound of the delay. However, it is difficult to analyze the models, and most results are still hard to compute and are unintuitive.

The objective of this paper is to estimate the delay bounds of a data acquisition system based on the line topology switched Ethernet. The reason for selecting line topology is as follows: firstly, line topology is basic and common in factory use; secondly, its performance is usually worse than that of other topologies because of the cascade switches, and therefore, it could act as a reference; lastly, it is easy to be described.

The main aim of this paper is to derive a rather concisely analytical result that would facilitate estimation of the real-time performance of line topology networks. We also introduce an approach of applying network calculus to switched ethernet to avoid the pay burst only once phenomenon and thereby simplify the calculation.

2 Network calculus

2.1 Overview

Network calculus is a newly developed theory based on min-plus algebra. It is now widely used to assess the real-time performance of communication networks. It is based on the fundamental work of \([12, 13]\) and has been fully developed in \([14]\). This theory is tailored to the analysis of switched networks used in industrial scenarios. On one hand, this theory models all network elements as nodes and data flows. Networks on buses, such as conventional Ethernet, are difficult to describe using these elements. However, switched networks are suitable in this case. On the other hand, from certain reasonable assump-
ations about input data flows and service node activities, network calculus provides deterministic results on network delays, backlogs, and throughputs; it is different from the conventional methodology that uses stochastic process theory. This property is very important in industrial usage, which requires a strong QoS guarantee.

2.2 Basic concepts and results

The basic concepts of network calculus include the arrival curve, service curve, and min-plus convolution/deconvolution. Here, only some basic and related concepts are covered to clarify the notations below; readers may consult [14] for a full introduction.

Arrival curves quantify constraints on the number of packets or the number of bits that flow in a time interval at a service node. Let $F$ be a data flow and $R(t)$ be the number of packets or bits of $F$ arriving in the time interval $[0, t]$. We say that the flow is constrained or has an arrival curve $\alpha(t)$ if for all $0 \leq s \leq t$,

$$R(t) - R(s) \leq \alpha(t - s)$$

(1)

where $\alpha(t)$ is a non-negative and non-decreasing function.

A service curve describes the service of flow $F$ in a node, which is a work station or a switch. Let $R'(t)$ be the amount of data output in a time interval $[0, t]$. Then, the non-negative, and non-decreasing function $\beta(t)$ is called the service curve for $F$ in this node if for all $t \geq 0$,

$$R'(t) \geq R \otimes \beta(t) = \inf_{0 \leq s \leq t} \{R(s) + \beta(t - s)\}$$

(2)

where $\otimes$ denotes the convolution operator. The output flow is constrained by the arrival curve $\alpha \otimes \beta(t) = \sup_{0 \leq s \leq t} \{\alpha(t + s) - \beta(t)\}$

(3)

where $\otimes$ denotes the deconvolution operator.

The constraints given by the arrival and service curve for a flow suffice to calculate an upper bound on the delay of a packet or bit in the service node. The delay is bounded by the horizontal distance between $\alpha$ and $\beta$:

$$delay \leq \sup_{t \geq 0} \{\inf \{s \geq 0 : \alpha(t) \leq \beta(t + s)\}\}.$$

(4)

There is a specific result in network calculus on a service node serving two or more flows according to a first come first serve (FCFS) strategy. Consider a lossless node serving two flows in the FCFS order. Denote these two flows by $F_1$ and $F_2$, with arrival curves $\alpha_1$ and $\alpha_2$, respectively. Assume that the node guarantees a service curve of $\beta$ to the aggregate of the two flows. Thus, $F_1$ is guaranteed by the service curve

$$\beta_1(t) = \begin{cases} [\beta(t) - \alpha_2(t - \theta)]^+ & \text{for } t > \theta \\ 0 & \text{for } 0 \leq t \leq \theta \end{cases}$$

(5)

where $[x]^+$ denotes $(x + |x|)/2$. Conventionally, this property is called FCFS splitting.

The widely used arrival curve for describing a data flow is the leaky bucket arrival curve. It is defined by $\alpha(t) = rt + b$ for $t > 0$, and 0 otherwise. Having a leaky bucket arrival curve allows a source to send $b$ bits at once, but without exceeding $r$ bit/s over the long run. Service curves of switches are mostly defined by $\beta(t) = C \cdot [t - T]^+$, which is called the rate-latency service curve. Data is delayed by a fixed time $T$ and then routed out at a rate $C$. In reality, this service curve only represents one output port of a switch. These two curves are popular because of their simplicity. We will also apply these in our analysis.

2.3 Pay burst only once principle

Consider two systems with service curve $\beta_1$ and $\beta_2$. What happens when a flow transverses the two systems in sequence? Boudec and Thiran[14] showed that the concatenation of the two systems offered an effective service curve of $\beta_1 \otimes \beta_2$ to the flow. Consequently, there are two ways to obtain the delay bounds:

1) by applying the network service curve;
2) by iteratively applying the individual bounds on every node.

The result obtained by the latter approach is always greater than that of the former. This is because the delay due to the burstiness of the input flow is calculated twice; this phenomenon is called pay burst only once. While using network calculus to obtain the end-to-end delay of a large system, it is important to apply the pay burst only once principle.

However, the use of this principle has two disadvantages. First, there is no universal approach to tell us how to apply this principle. People have to try their best to use this principle wherever they can. Second, the analysis of a large network becomes very difficult and always yields intricate results[15,16]. In the next section, a novel approach is raised to analyze switched Ethernet without the interference of the pay burst only once phenomenon.

3 Switched Ethernet analysis

3.1 State of art in Ethernet switches

A switch can be functionally considered as a multiport bridge. However, it is more powerful than a conventional bridge due to its application specific integrated circuit (ASIC) based architecture and its ultra-rapid simultaneous multiple access memory. At present, high-performance switches are increasingly replacing conventional hubs. Commercially available switches from various manufacturers have the following technical properties in common.

- Store-and-forward. There are mainly three switch fabrics. They have shared memory, matrix, and bus. Shared memory is the most popular architecture; it can avoid the head of line (HOL) blocking. By using shared-memory, packets are always processed in the store-and-forward mode.
- Work-conserving. Switches will route out the packets received as soon as possible. They make full use of their output ports until their buffers are empty.
- First come first serve (FCFS) and priority queueing (PQ) strategies. When there are two flows originating from different ports but requiring the same output