TITLE

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Abstract—**When multiple computational elements are involved to handle an event in a cyber-physical system, the communication delay between these elements contributes significantly to the worse case end-to-end response time of that event. In a real-time distributed system where computing nodes are connected via network, modeling the property of the network, such as the shared bandwidth and the burstness of traffic, is a challenge in order to model and bound the worse case end-to-end response time. In this work, we employed traffic control on these computing nodes to limit network contention, and utilized linear programming model to analyze the worse case network delay under the assumption that traffic forwarding paths are predefined. In addition, we implemented a real-time distributed storage system on the basis of distributed hash table algorithm to provide data storage service with bounded response time. Our real-time distributed storage system is evaluated on a cluster of nodes in a fully switched network, and the results demonstrate that it is able to provide real-time bounded storage service with the network performance isolation provided by the traffic control.**

I. Introduction

When the computational elements in a cyber-physical system are connected by wide-area networks, understanding and controlling the network behavior become an essential part in order to provide real-time monitoring and control of the physical entities. For example, we have proposed to develop a distributed Wide-Area Measure System to monitor and control the state of the North American power grid. The current state-of-art monitoring architecture utilizes one centralized Phasor Data Concentrator to process the data collected by all phasor monitors, e.g., Phasor Measurement Units. The centralized data concentrator will soon become a bottleneck as the number of monitors is increasing extremely fast nowadays. [**?**], [**?**], [**?**]. In the proposed distributed architecture, multiple data concentrators are deployed to different geographic areas, e.g., the Eastern interconnection area, to process real-time monitoring data. These phase monitors and concentrators cooperate to monitor and optionally control the state of the power grid. Since the control operations to the power grid rely on multiple monitors and concentrators, the communication delays between them have significant effect on the design of power grid monitoring and control algorithm. Thus, a bounded worst case network delay is required to determine the effectiveness of upper-layer control algorithms.

Network congestion is a big trouble of modeling network delay, especially in a network communication intensive cyber-physical system. For example, phasor monitors work at 50/60 Hz, which periodically generates a burst of data to be transmitted through the network. The frequent burst of data may induce severe network congestion if they are sent into the network simultaneously by multiple phasor monitors and concentrators, even though the power grid system utilizes proprietary Internet backbones to transmit data. Network congestion may increase the packet queueing delay on intermediate network devices, and require retransmission of that data, which results in large variation of network delay. A straightforward way to alleviate network congestion is to control the burstiness of the data.

In one respect, this is a resource sharing problem. The resource here is the network bandwidth. In terms of resource sharing among parallel computation units, a few research projects have their focus on shaping the resource access by all units into well defined patterns, so these units collaborate to reduce the variation of resource access cost. For example, MemGuard[**?**] shapes the memory access by each core in modern multi-core platforms in order to share memory bandwidth in a controlled way so that the memory access latency is bounded. D-NoC[**?**] shapes the data transferred by each node on the chip with a (σ, ρ) regulator[**?**] to provide guaranteed latency of data transferring on the processor. Thus, we propose to utilize traffic control integrated in Linux to regulate the data sent into the network on each distributed node, in order to reduce the bandwidth contention. However, network traffic is different from aforementioned memory access traffic and node-on-chip data transfer in terms of the capability of control to the computation units that the traffic is transmitted through. The behavior of intermediate network devices that have no traffic regulator employed, e.g., switches, also have large impact on the end-to-end network delay.

Thus, in the other respect, this is a worst case execution time analysis problem. The worst case network delay is required to be modeled under the situation that the data sent by the end nodes are regulated by the traffic control policy and that the network topology is known as a priori. Many stochastic models have been utilized to model the network traffic, including Poisson process based models[**?**] and lately self-similar models[**?**]. We propose to use linear programming models, since the worst case network delay is more concerned in the real-time situation.

We implemented a real-time distributed storage system that provides storage service with bounded response time by shaping the traffic and modeling the network delay. This system is utilized to support the power grid state monitoring and control in the decentralized architecture. Our idea is to use distributed hash table (DHT) algorithm to map the data with the storage node, so that the phasor monitors could store the latest data into the system and the concentrators could fetch data from the system by using DHT algorithm to locate the node in which the data is stored. We applied our network delay model on this distributed storage system to analyze the time bound for the data lookup service, and evaluated the model by comparing it with the time measured in our experimental environment.

In summary, the contributions of this work are: (1) utilizing the traffic control to alleviate network bandwidth contention in a real-time distributed storage system, which is network traffic intensive; (2) using linear programming model to analyze the worst case network delay in a general network topology; (3)

evaluating our real-time distributed storage system in a cluster of nodes to show the effectiveness of the traffic control and our model.

The rest of the paper is organized as follows. Section **??** presents the design of our real-time storage system and traffic control policy. Section **??** presents our timing analysis model. Section **??** presents the evaluation results. Section **??** presents the related work. Section **??** presents the conclusion and on-going part of our research.