Combining Measurements and Network Calculus in Worst-Case Delay Analyses for Networked Cyber-Physical Systems

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***Abstract*—Recently, switched Ethernet has become increasingly popular in networked cyber-physical systems (NCPS). In an Ethernet-based NCPS, network-connected devices (e.g., sensors and actuators) realize time-critical tasks by exchanging miscellaneous information, such as sensor readings and control commands. To ensure reliable control and operation, network-induced delays for time-critical NCPS applications must be carefully examined. In this work, we propose a framework combining network delay measurements and network-calculus-based delay performance analysis to obtain accurate, deterministic worst-case delay bounds for NCPS. By modeling traffic sources and networking devices (e.g., Ethernet switches) through measurements, we establish accurate traffic and device models for network-calculus-based analysis. To obtain worst-case delay bounds, different network-calculus-based analytical methods can be leveraged, allowing CPS architects to customize the proposed delay analysis framework to suit application-specific needs. Our evaluation results show that the proposed approach derives accurate delay bounds, making it a valuable tool for architects designing NCPSs supporting time-critical applications.**

I. Introduction

As digital computing and communication technologies become increasingly integrated into physical systems, it is of urgent necessity to design network infrastructure supporting reliable, low-latency communication among sensors and actuators distributed in physical environment. Recently, switched Ethernet has become increasingly popular in networked cyber-physical systems (NCPS) such as power substation automation systems [1] and avionic systems [2], [3]. In an Ethernet-based NCPS, network-connected devices realize a wide range of tasks by exchanging miscellaneous and sometimes mixed-criticality information (e.g., sensor readings, control commands, and synchronization messages) with each other. To ensure reliable control and operation, network-induced delays for time-critical and/or delay-sensitive applications of an Ethernet-based NCPS must be carefully examined.

In many Ethernet-based NCPSs, publisher-subscriber messaging model is adopted to enable flexible, real-time communication among sensors, actuators, and controllers. NCPS applications employing the publisher-subscriber model includes power substation automation system based on IEC 61850 [1], Avionics Full-Duplex Switched (AFDX) Ethernet [2], [3], and automotive networks [4]. In a practical Ethernet-based NCPS, one or more communication protocols/standards may be implemented for different applications. When network-based applications are implemented, network traffic pattern on

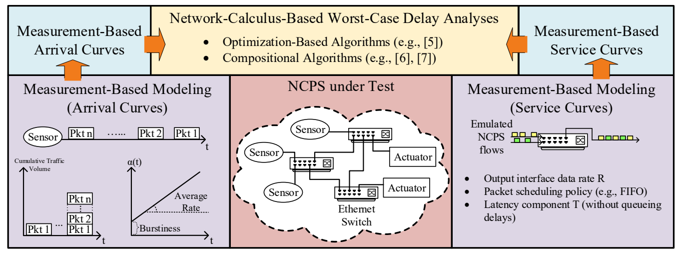

Fig. 1. Overview of the proposed framework.

an NCPS (i.e., how each device is connected to other devices, flows generated by each device, and traffic profile of each flow) can also be determined (e.g., based on application and device specifications). To ensure that real-time performance of various time-critical applications are met, it is of vital importance to find the worst-case delay bounds on network-induced delays experienced by their network traffic flows. However, existing worst-case delay analysis algorithms (e.g., [5], [6]) are evaluated using specification-based models, and little has been done to facilitate the evaluation of existing and emerging methods in realistic NCPS settings.

In this work, we improve and extend the framework proposed in [7] to facilitate worst-case delay analysis of Ethernet-based NCPSs. In contrast to tightening delay bounds through designing sophisticated delay bounding algorithms, our framework finds tighter bounds on network-induced delays through the use of realistic, measurement-based models. Therefore, both existing and emerging network-calculus-based delay bounding algorithms can be integrated into our framework to derive delay bounds for real-world NCPSs, enabling NCPS architects to choose proper method(s) to balance between tightness of bounds and computational complexity.

II. Approach

Given the traffic pattern of an Ethernet-based NCPS, our proposed framework (see Figure 1) first extracts traffic characteristics of network-connected devices and establishes arrival curve models. Then, emulated traffic flows are injected into networking devices of the NCPS (e.g., Ethernet switches) and network-calculus-based device models (i.e., service curves) are constructed. Finally, network-calculus-based analytical method(s) will be chosen and measurement-based models will be integrated to find worst-case delay bounds.

A. Measurement-Based Modeling

To perform network-calculus-based analysis, arrival curves of network-connected devices and service curves of networ-

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king devices need to be established. To establish the arrival curve of a device (e.g., a leaky-bucket curve $\alpha(t)=\sigma+\rho\cdot t$, where σ is the burstiness component and ρ is the average rate), two different measurement approaches are supported:

1) *Direct Measurements*. Using Ethernet taps or taking measurements from test equipment with the same configuration as the device of interest, we obtain network packets generated by the device and timestamps at the traffic capture device. By applying the definition of arrival curve, burstiness and average rate components can be straightforwardly derived (see Figure 1).
2) *Specification-Based Emulation*. When actual measurements cannot be easily taken (e.g., in early stage of NCPS design where devices and equipment have not been procured, or a physical device is in operation and cannot be interrupted), we can emulate the device based on its control system specifications (e.g., sampling rates of sensors and communication protocol utilized). Then, direct measurements are taken from the emulated device and arrival curve model is established.

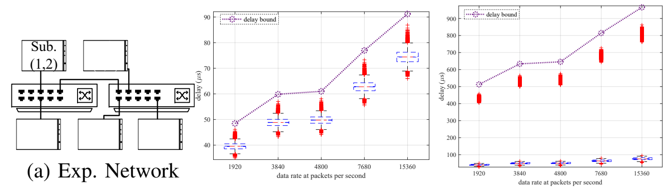
To obtain service curve of a networking device (e.g., a rate-latency curve $\beta(t)=\max\{0,R(t-T)\}$, where R is the rate component and T is the latency component), rate component can be determined from device specifications. However, the latency component must be measured by injecting packets at low rates such that queueing does not occur in the device. This is because T models non-queueing delays incurred by the device. Packet sizes of different traffic sources can be taken into account if differences in packet sizes are significant (e.g., an NCPS simultaneously transmitting packets as short as 64 bytes and as long as 1500 bytes). This can be done by incorporating a packetizataion term in the service curve model, e.g., $\beta(t)=\max\{0,R(t-T)-l_{max}\}$, where l_{max} is the maximum packet size of the flow of interest.

B. Network-Calculus-Based Analysis

In practical NCPS design, real-time requirements for all the time-critical tasks need to be verified. Once a specific network-calculus-based delay analysis algorithm (e.g., [5]–[7]) is chosen, delay bounds are computed for traffic flows associated with all the time-critical applications. If delay bound for a particular flow exceeds its required worst-case delay, the NCPS design should be further refined. It should be noted that early work on network-calculus-based analysis finds that certain algorithms can generate formally provable bounds that are overly pessimistic. Therefore, extra network measurements based on application-specific traffic pattern can be taken (e.g., at Ethernet switch output interfaces [7]) and models refined with measurements can be adopted to replace intermediate network-calculus models and produce realistic worst-case delay bounds.

III. Evaluation

We emulate an NCPS with a publisher-subscriber traffic pattern shown in Figure 2a, which has been seen in various application domains (e.g., [1], [2], [4]). Both Ethernet switches are equipped with 100-Mbps interfaces. Three publishers (i.e.,



(a) Exp. Network (b) Experiment I (c) Experiment II

Fig. 2. Experiment network topology and preliminary evaluation results.

Pub. 1, Pub. 2, and Pub. 3) generate time-critical traffic flows and two subscribers consume the data (e.g., the subscriber on the left subscribes to flows from Pub.1 1 and Pub. 2). We use netFPGA NICs to perform traffic capture and packet time-stamping. Network-calculus-based analytical method used in our experiments is the same as [7].

Currently, two experiments are conducted to evaluate the quality of delay bounds obtained by our framework. In Experiment I (see Figure 2b, all network-connected devices generate packets with the same size (192 bytes). Our results show that the proposed approach can generate sufficiently tight bounds, which is only slightly greater than the worst-case delays observed. In Experiment II (see Figure 2c), packet size for each network-connected devices is variable (between 64 and 1500 bytes) and packetization effect is taken into account. Although the derived bounds are acceptably tight, it is evident that these bounds deteriorate due to intrinsic pessimism that comes with the packetized models.

IV. Conclusion

We propose a worst-case delay analysis framework for NCPS and show that measurement-based modeling can improve the quality (i.e., tightness) of delay bounds. Further enhancements to our framework to limit pessimism of certain network-calculus models will be explored in the future.

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