

Deadline-aware Routing with Probabilistic Delay Guarantee in Cyber-Physical Systems

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Abstract—In this paper, we propose a deadline-aware routing algorithm that considers a probabilistic delay constraint with a pre-specified deadline for cyber-physical systems (CPS). Most routing algorithms minimize a certain average performance metric such as mean delay. Whereas, our proposed routing algorithm can route traffic to maximize the probability reached within a given deadline by considering the delay distribution rather than the mean delay only. Therefore, our algorithm can enhance the quality of control (QoC) of networked control in CPS. We analyze the proposed routing algorithm by using the queueing delay distribution when the single hop delay follows exponential distribution. We then construct a network topology and carry out simulation to evaluate the performance of the proposed scheme. Our simulation results show that the proposed routing algorithm can effectively increase the probability of delay reached within the deadline and can improve the performance of networked control in CPS.

I. INTRODUCTION

Network delay is a key issue in quality of service (QoS) of network applications. In particular, the recent advent of cyber-physical systems (CPS) requires timely delivery of packets because CPS generally has real-time feedback control loops for physical systems via networks as shown in Fig. 1 [1]. In other words, a certain level of quality of control (QoC) needs to be satisfied in CPS to provide reliable real-time control services, and network delay is a critical factor for QoC.

By contrast, most routing algorithms use the minimum mean delay as a routing metric [2]. In terms of CPS performance, it is insufficient to minimize the mean delay. Since real-time networked control requires timely delivery of packets, what is more critical is whether each packet arrives within the deadline or not. Consequently, under the stochastic nature of network delay, we need to introduce a performance metric such as the probability that the delay of each packet is below the deadline.

In this paper, we propose a deadline-aware routing algorithm that considers the probability of packet delivery within the deadline as a performance metric. The key idea is to exploit the fact that the end-to-end path with the minimum mean delay is not always the same as the one that maximizes the probability of packet delivery within the deadline. For example, a path with the minimum mean delay can give poor packet delivery performance within the deadline if the delay variance of the path is comparably larger than other paths. Hence, we focus

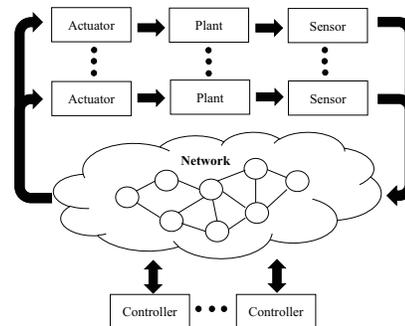


Fig. 1. Networked control architecture in cyber-physical systems.

on the QoC of CPS and propose a routing algorithm that can improve the control performance over networks.

In the network literature, QoS routing has been extensively studied. For example, in [2], [3], multiple performance metrics such as bandwidth, delay, jitter, and packet loss are considered. QoS routing in wireless networks has been also widely studied [4]. In addition, a lot of topology control algorithms that minimize interference among nodes are proposed for QoS requirements [5]. In the meantime, in the transportation literature, a stochastic vehicle routing algorithm is proposed in [6], which exploits the idea of outage probability within the deadline as in this paper.

The rest of the paper is organized as follows. In Section II, we introduce our key idea and propose a deadline-aware routing algorithm. Then, in Section III, we carry out simulation for performance comparison of the proposed algorithm with conventional shortest path routing. In particular, we show the effect of routing on the performance of networked control. Finally, in Section IV, we give our conclusion and a possible direction of future work.

II. DEADLINE-AWARE ROUTING

A. Key Idea

As already mentioned, networked control in CPS needs timely delivery of each packet rather than average performance. More specifically, typical digital control periodically reads from sensors and sends out control input to the physical systems. Hence, whether or not packets are delivered within the pre-specified deadline is critical for the performance as

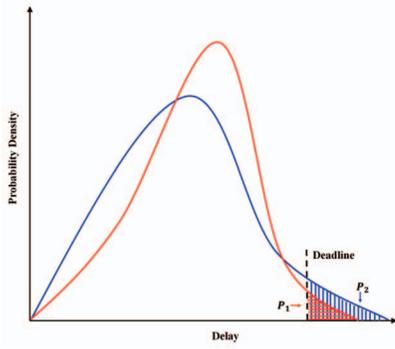


Fig. 2. Comparison of outage probability of two different density functions: Larger mean with smaller variance (red) vs. smaller mean with larger variance (blue).

well as the stability of the physical systems in CPS. This requirement is fundamentally different from those average performance requirements such as average delay and average throughput for best-effort traffic. To this end, due to the stochastic nature of network delay, we need to consider a probabilistic metric of the probability that each packet is delivered within a given deadline.

Fig. 2 illustrates two probability density functions, one with larger mean and smaller variance (red line) and the other with smaller mean and larger variance (blue line). The probability that delay is larger than a given deadline, i.e., $\text{Prob}(\text{delay} > \text{Deadline})$, is respectively denoted as P_1 for the red line and P_2 for the blue line. In the figure, it is obvious that P_1 is smaller than P_2 . From this observation, we can conclude that a path with the minimum mean delay will not always give the maximum probability of satisfying the deadline. Hence, instead of minimizing the mean delay, we focus on minimizing the outage probability that the network delay is larger than the deadline.

B. Deadline-aware Route Selection

Here, we assume that the queueing delay distribution of a single hop link follows the exponential distribution, which is practically reasonable as follows: The single hop delay from a backbone network is measured in [7], which gives that the queueing delay is exponentially distributed by gathering packets through a router. In [8], the link-level queueing delay distribution is shown to be exponentially distributed.

In order to sum up the delay of each link to get the end-to-end delay distribution, we use a hypo-exponential distribution. First, the delay at each link i is assumed to be exponentially distributed with its own rate of λ_i . Then, the end-to-end delay distribution is expressed as a sum of independent exponential distributions as follows:

$$X = \sum_{i=1}^n X_i, \quad (1)$$

where X is a hypo-exponential random variable, and X_i is an exponential random variable with rate of λ_i .

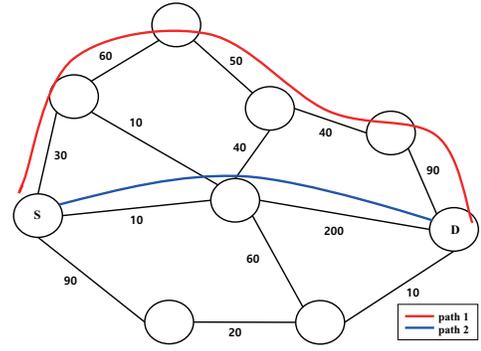


Fig. 3. A network topology for performance evaluation. It should be noted that the number on each link denotes the rate λ and hence the mean delay of each link is $1/\lambda$.

Here, the mean and variance of the end-to-end path delay in (1) can be calculated as follows:

$$X_{mean} = \sum_{i=1}^n \frac{1}{\lambda_i}, X_{var} = \sum_{i=1}^n \frac{1}{\lambda_i^2}.$$

Then, we can calculate the probability that the end-to-end delay is within the deadline by using the following cumulative distribution function (CDF) of the hypo-exponential distribution.

$$\text{Prob}(X \leq x) = F(x) = \sum_{i=1}^n \frac{e^{-\lambda_i x} \prod_{j=1, j \neq i}^n \lambda_j}{\prod_{j=1, j \neq i}^n (\lambda_j - \lambda_i)}, \quad (2)$$

where λ_i and λ_j respectively denote the rate of link i and link j . Based on the probability obtained from (2), we can select a route for each source-destination pair among possible candidates.

III. PERFORMANCE EVALUATION

In this section, we evaluate our algorithm with Simulink and MATLAB [9]. The network topology for performance evaluation is given in Fig. 3, where the number on each link denotes the rate λ of the exponential distribution. It should be noted that the mean delay of each link is $1/\lambda$. Here, path 1 and path 2 are the end-to-end routes determined by the proposed stochastic routing algorithm and the conventional shortest path routing algorithm, respectively.

By using (1), we can calculate the statistics of each path 1 and path 2, i.e., (X_{mean}, X_{var}) pair as follows: path 1 has $(0.1061, 0.0025)$ and path 2 has $(0.105, 0.01)$. The shortest path routing selects path 2 because it gives a smaller mean delay while the proposed scheme selects path 1 to minimize the outage probability.

Fig. 4 shows the CDFs of path 1 and path 2. We set 200 ms as a deadline for the network delay. Under this condition, the probability of the packet delay within the deadline is 0.9493 for path 1 and 0.8575 for path 2, respectively. Although the mean delay of the two paths are similar, the outage probability of packet delivery can be significantly different.

To further elaborate the effect of outage probability on networked control in CPS, we consider networked control as

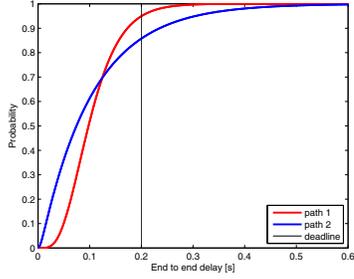


Fig. 4. The CDF of path 1 and path 2.

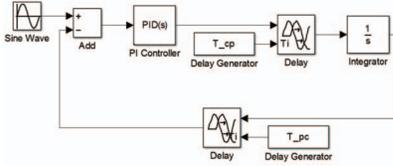


Fig. 5. A Simulink model of networked control.

shown in Fig. 5, where we use the network delay generated from the network topology in Fig. 3. As a practically meaningful physical system, we use an integrator plant frequently found in many industrial applications, and we consider a proportional-integral controller as a typical control algorithm, where the proportional gain and the integral gain are set to 3 and 1, respectively. The reference signal is a sine wave with an amplitude of 1 and a frequency of 2 rad/sec. The objective of networked control is to make the output of the system tracks the sine wave. Here, the network delay is inserted to simulate the effect of networked control. The sampling time of the controller is set to 10 ms. The delay of the networked control system consists of T_{cp} and T_{pc} , where T_{cp} denotes the delay from the controller to the plant; T_{pc} denotes the delay from the plant to the controller.

Fig. 6 shows the mean square error (MSE) between the reference and the actual output for path 1 and path 2, respectively. The runtime of each simulation is 10 seconds, and the number of simulation runs is 1,000. The average MSE of path 1 and path 2 are 0.1735 and 0.1903, respectively. Since path 2 gives a larger outage probability of delay, it gives much worse control performance than that of path 1.

In summary, our simulation results confirm that the proposed algorithm shows better control performance than the conventional shortest path routing scheme in CPS. In order to improve networked control performance in CPS, we need to consider not only the average network behavior, but also the probabilistic nature.

IV. CONCLUSION AND FUTURE WORK

In this paper, we have proposed a deadline-aware routing algorithm to satisfy a probabilistic delay constraint. The objective of the proposed routing algorithm is to maximize the probability of packet arrival within the deadline. Our simu-

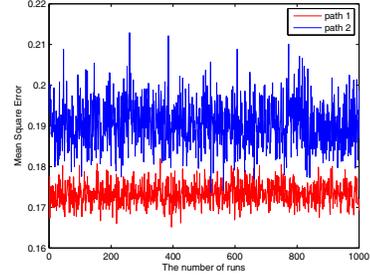


Fig. 6. The mean square error of networked control with path 1 and path 2.

lation result shows that the proposed algorithm significantly improves performance of networked control compared to the shortest path routing algorithm.

One possible direction of future work is to take into account system robustness [10]. Since the obtained delay distribution may contain a certain level of uncertainty, it is needed to consider a robust design approach under this uncertainty.

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