Master's Thesis
석사 학위논문

Deadline-aware Routing: Quality of Service Enhancement in Cyber-Physical Systems

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Department of Information and Communication Engineering

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by

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A thesis submitted to the faculty of DGIST in partial fulfillment of the requirements for the degree of Master of Science in the Department of Information and Communication Engineering. The study was conducted in accordance with Code of Research Ethics[1].

11. 25. 2016

Approved by

Professor Kyung-Joon Park (Signature)
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Professor Jonghyun Kim (Signature)
(Co-Advisor)

[1] Declaration of Ethical Conduct in Research: we, as a graduate student of DGIST, hereby declare that we have not committed any acts that may damage the credibility of my research. These include, but are not limited to: falsification, thesis written by someone else, distortion of research findings or plagiarism. We affirm that my thesis contains honest conclusions based on my own careful research under the guidance of my thesis advisor.

Deadline-aware Routing: Quality of Service Enhancement in Cyber-Physical Systems

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Accepted in partial fulfillment of the requirements for the degree of Master of Science

11. 25. 2016

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ABSTRACT

This paper proposes a deadline aware routing algorithm that considers a probabilistic delay constraint with a pre-specified deadline for cyber-physical systems (CPSs). Most routing algorithms typically minimize a performance metric, such as mean delay. However, minimum mean delay is an insufficient routing metric, because deadline sensitive systems require timely delivery. The proposed routing algorithm maximizes the probability of achieving a given deadline by considering the delay distribution rather than the mean delay. Therefore, the algorithm can enhance the quality of control of networked control in CPSs. We assess the proposed routing algorithm where the single hop delay follows an exponential distribution, then construct a network topology and perform simulations to evaluate the algorithm's performance. The simulation results show that the proposed routing algorithm can effectively increase the probability of meeting the deadline and improve networked control performance in CPS.

Keywords: Routing algorithm, Cyber-physical systems, network delay, variance, control performance

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I. INTRODUCTION

Network delay is a key issue that influences networking Quality of Service (QoS). In particular, cyber physical systems (CPSs) have been recently developed and widely researched. CPSs require timely packet delivery, since the employ real time feedback control loops, with a physical system being controlled via the network [1]. Therefore, network delay is a significant factor for QoS and Quality of Control (QoC) for delay sensitive systems, such as real time system, networked control system (NCS) [2], and CPS.

Packets follow a routing path from source to destination based on the network policy. Delay traversing the routing path is called network delay, which includes deterministic and non-deterministic delays. Deterministic delays are caused by hardware performance issues, e.g. routers, whereas non-deterministic delays depend on software performance, such as routing algorithms, etc.

The routing algorithm reflects the system objectives and includes the chosen optimization metric, which is usually mean delay [3]. However, minimizing the mean delay is not sufficient enough to achieve the performance of CPS since probability of packet arrival within given deadline is more important in real-time networked control such as CPS.

Therefore, we propose a deadline-aware routing algorithm that considers the probability of packet arrival within a given deadline as the major metric. Minimum mean delay does not maximize the probability of packet arrival within the deadline. For example, suppose a routing path, R1, has the same minimum mean delay but higher delay variance compared to another path, R2. Then R1 may not be able to deliver a sufficient number of packets to the destination within a given deadline. Therefore, we focus on the QoC of CPS, and propose a routing algorithm that can improve control performance over networks**.**

The rest of the paper is organized as follows. We introduce background fundamental details in Section 2, to illustrate how the proposed solution contributes to improving network performance. Section 3 reviews current research related to network packet transport and development of the proposed routing algorithm. In Section 4, we explains the key concepts and motivations, and presents the proposed deadline-aware routing algorithm. Section 5 presents the parameters and structures for a simulation model to test the proposed algorithm, and compares the performance with respect to the conventional shortest path routing algorithm. In particular, we show the effect of routing on networked control performance. Finally, we summarize the outcomes and present our conclusions in Section 6.

2. BACKGROUND

2.1 Network Delay

Network delay represents the elapsed time from when a packet leaves to sources until it reaches its final destination, passing through the various nodes and other elements of the network. The packet experiences various processes as it is delivered to various network devices in the route. Figure 2.1 shows the types of delay that can occur during packet delivery, including processing (D_{proc}), transmission (D_{trans}), propagation (D_{prop}), queueing (D_{queue}), nodal (D_{nodal}), and end to end ($D_{end-end}$) delays.

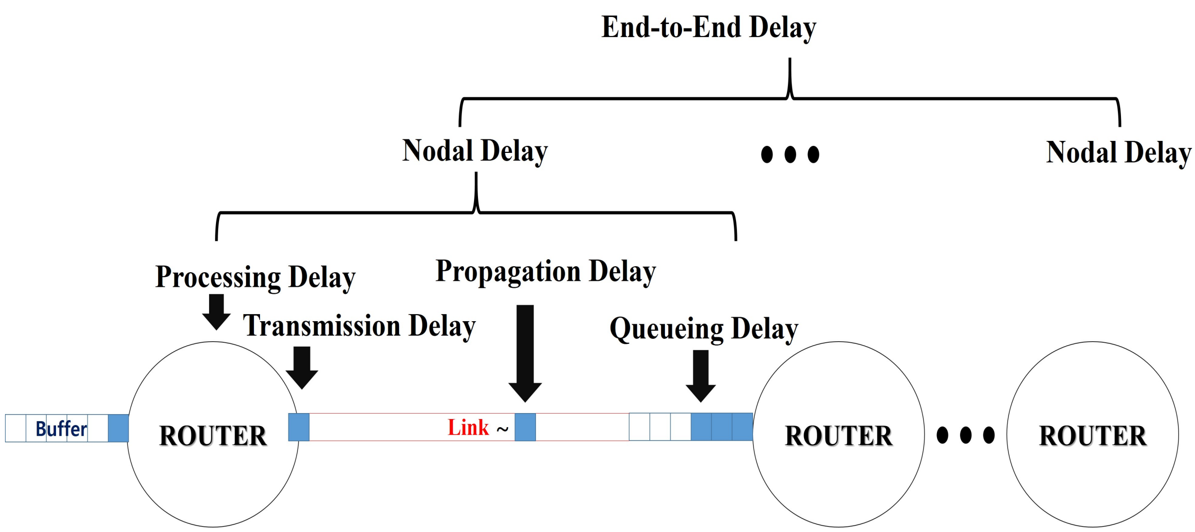


Fig. 2.1. Types of network delay

Processing Delay

D_{proc} represents the time for a router to check whether received the packet includes an error, and to decide where it will be sent by checking IP header.

Transmission Delay

D_{trans} [sec] represents the time for all bits to be pushed up to the transport link. This delay is a consequence of the link data rate (*R*) [bits per second] and packet length (*N*) [bits].

$$D_{trans} = \frac{N_{bits}}{R_{bps}}\ sec.$$

Propagation Delay

D_{prop} [sec] represents the time for an electric signal to be transported between from one router to another. This delay varies depends on the medium of the link, the distance (*D*) [m] and speed (*S*) [m/s],

$$D_{prop} = \frac{D_m}{S_{m/s}}\ sec.$$

Queueing Delay

Routers use buffers to process many packets simultaneously. D_{queue} [sec] represents the wait time of an incoming packet until the previous packet is processed in the buffer. If the buffer is empty, D_{queue} = 0, but in general D_{queue} varies with the number of packets in the buffer, and the router processing speed. Thus, D_{queue} is a non-deterministic delay, in contrast to the other delays discussed here.

Nodal Delay

D_{nodal} [sec] is the sum of delays occurring from one router to the next. D_{nodal} varies on link conditions, such as data rate, distance, and packet length. Therefore, D_{nodal} can differ even when measured on the same link,

$$D_{nodal} = D_{proc} + D_{trans} + D_{prop} + D_{queue}.$$

End-to-End Delay

$D_{end-end}$ [sec] is the sum of D_{nodal} from source to destination, but is not the product of all D_{nodal} values, due to their non-deterministic characteristics (arising from D_{queue}),

$$D_{end-e} = \sum_{i=1}^{n-1} D_{nodal}^{i} \ (n = the\ number\ of\ hops),$$

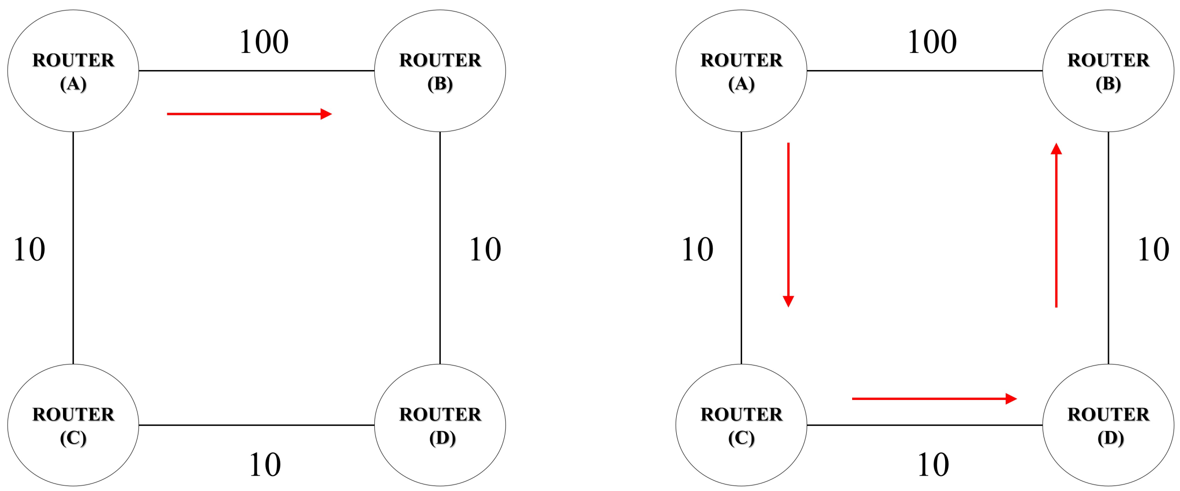
where n is the number of hops on the network route. Since D_{end-e} is the critical delay that affects end users, minimizing $D_{end-end}$ is the focus for routing algorithms [4].

2.2 Routing Protocols

The concept of routing is to allocate the optimal path from source to destination, which applies not only to computer networks, but also to roadways, etc. The optimal path varies depending on the metric employed. The metric is a calculated factor expressing the "cost" of a given route, and incorporates hop count, delay, bandwidth, reliability, and load. Thus, we may choose different optimal paths depending on the specific metric chosen, which may vary for different purposes.

Routing protocols are classified differently depending on their table management and information exchange methods. Table management methods include static, dynamic, and default routing. The network manager directly designates the path for static routing. This routing method is usually employed only when the network environment is static and relatively small, since the routing table is not changed unless the network manager intervenes. Dynamic routing updates modified information among routers automatically. Although this consumes more resource than static routing, unexpected malfunctions in any router or other network devices are actively resolved.

Information exchange methods are distance vector and link state routing protocols, as shown diagrammatically in Fig. 2.2. Distance vector protocol updates router information across the whole network specific, periodic, times. Hop count and vector to destination require relatively little effort to update. However, they should be updated periodically regardless of network change, which wastes network traffic. Moreover, it takes longer to update routers when the convergence time extends due to router malfunctions, because the update is executed by broadcast methods. Bellman-Ford [5] discuss a representative updating algorithm. In contrast to the distance vector protocol, link state protocol knows all the routing information to the packet destination, which provides short convergence time and infrequent information exchange. However, maintaining the entire routing information consumes significant memory. Dijkstra [6] presents and discusses a representative and popular algorithm.



(a) *Distance vector.* (b) *Link state.*

Fig. 2.2. Comparison of distance vector routing and link state routing.

Figure 2.2(a) shows that in distance vector routing, the optimal routing path is set as A-B, since the router only stores hop count and direction to destination. On the other hand, as shown in Fig. 2.2(b), the link state router knows the entire network information to the destination, and is able to optimize the routing path as A-C-D-B. Link state protocol is generally used for larger networks, and the proposed scheme follows this protocol.

2.3 Networked Control System

Figure 2.3 shows how the network control system (NCS) connects various devices in different locations via the network and exchanges control and input/output signals. The NCS is itself connected via the network, which reduces system maintenance costs by minimizing wire connections among related devices, and assists with system expansion and management due to network flexibility.

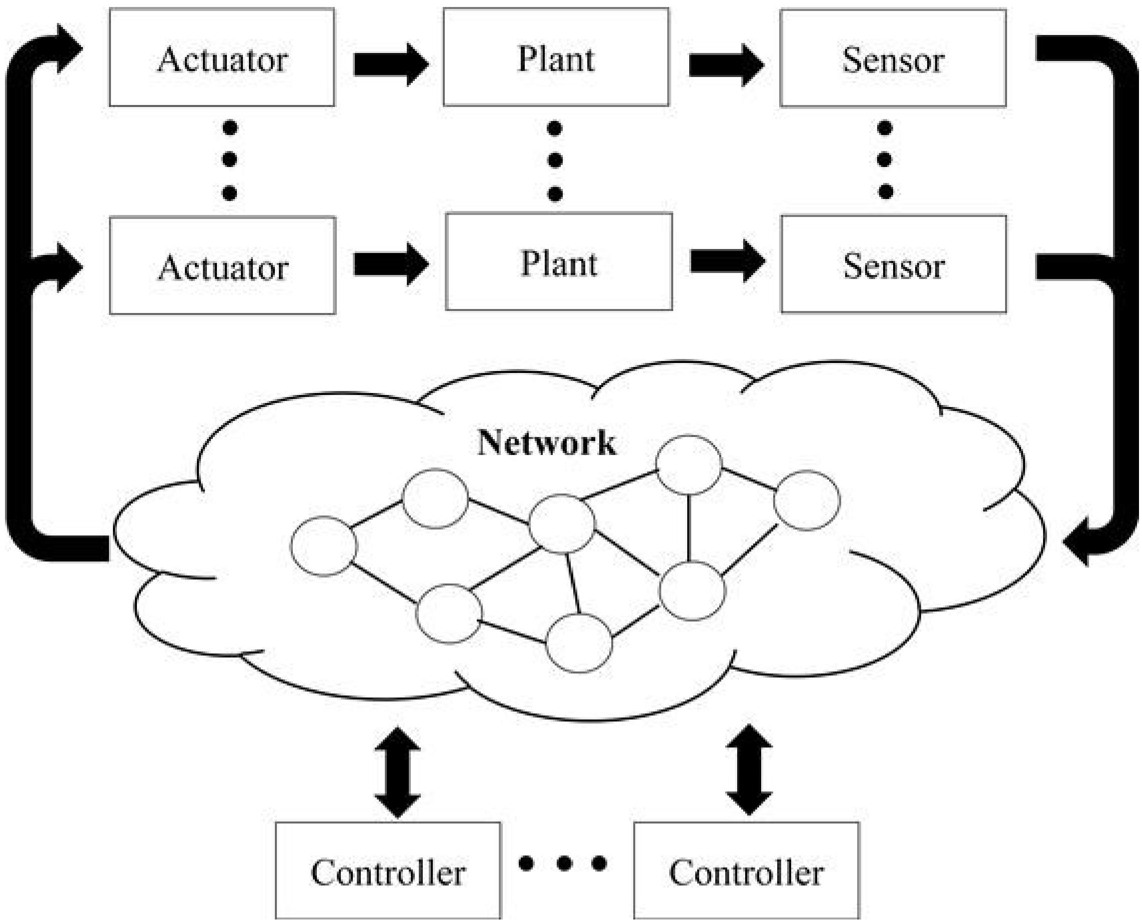


Fig. 2.3. Networked control system overview.

CPS is one of the most popular NCS models. It provides a feedback control system that affects the physical system based on observation from network connected systems. Since CPS is a real time system, it requires immediate responsiveness, and to guarantee this, it is essential to minimize network delay. QoS and QoC in CPS environments have been widely investigated.

3. RELATED WORK

Routing algorithms generally use packet transmission times for the network and builds a path decision using vehicle and plane concepts. To select a path, the algorithms chooses the desired metric, such as delay, bandwidth, packet loss, stability, or hop count, and calculates the optimal path by comparing the calculated metric for candidate paths. Most networks use the conventional shortest path routing algorithm with the minimum mean delay metric. This section discusses previous routing algorithm studies considering metric options.

3.1. Quality of service routing

Networked control has become increasingly powerful and popular, and hence, QoS routing has been extensively studied. Systems employing NCS are very broad, including healthcare, CPS, and industry. multiple performance metrics were considered in [3] and [7], and showed that although employing multiple metrics makes it more complex to calculate the optimal path, system performance can be significantly improved, with guaranteed QoS by considering bandwidth, delay, jitter, packet loss, and other metrics. In terms of robustness, path diversity routing for QoS was proposed [8]. QoS routing has also been widely studied in the context of wireless networks [9], and many topological control algorithms that minimize interference among nodes have been proposed [10].

3.2. Road networks

In transportation literature, a stochastic vehicle routing algorithm is proposed in [11]. They considered the delay distribution of real road network. This paper assumed that road network delay follows Gaussian distribution by gathering the real delay. In order to select the best path, this algorithm considered maximum probability reached within deadline based on [12], [13]. The algorithm then compare the distribution of pre-stored delay data in a database, and since the delay distribution is Gaussian, calculates the optimal path. We exploit this method for our proposed algorithm, migrating the broad principles of these algorithms into the computing network environment.

4. DEADLINE-AWARE ROUTING ALGORITHM

4.1. Key Idea and Motivation

As already mentioned, networked control in CPS requires timely delivery of each packet rather than average performance. The most important aspect is that a typical digital control periodically receives data from sensors and sends control inputs to the physical system. Thus, the probability of successful packet delivery within a given deadline is critical for system performance and physical system stability. This requirement is fundamentally different from average performance requirements, such as average delay and throughput for best-effort traffic. However, due to the stochastic nature of network delay, we need to consider a routing metric that incorporates the probability that each packet is delivered within a given deadline.

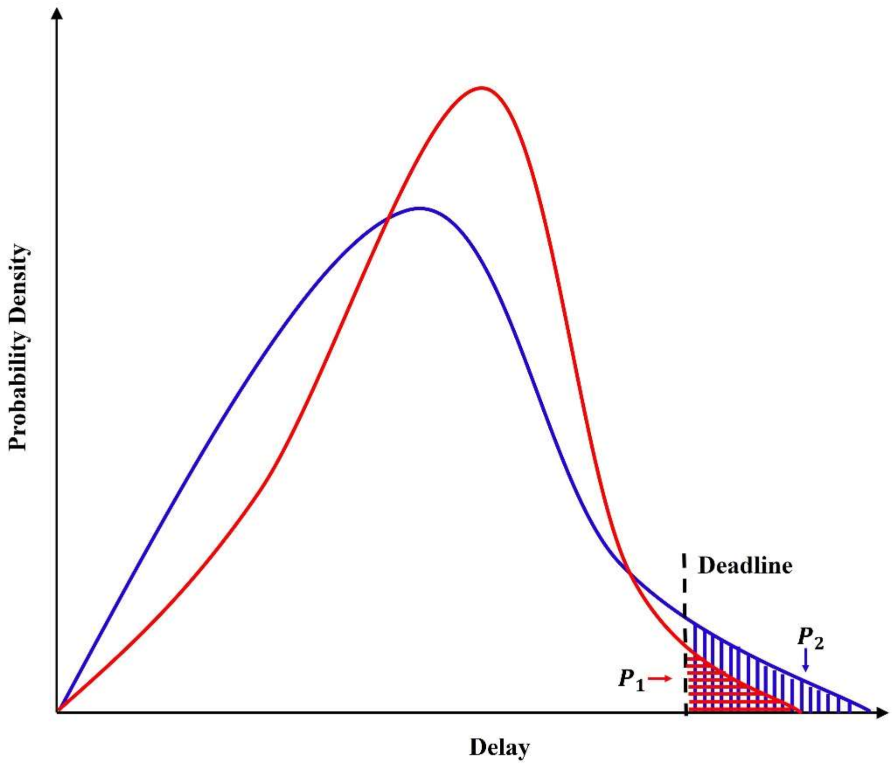


Fig. 4.1. Comparison of outage probability of two different density functions:
Larger mean with smaller variance (red) vs. smaller mean with larger variance (blue).

Fig. 4.1 shows two typical probability density functions (PDF), one with larger mean and smaller variance (red line), and the other with smaller mean and larger variance (blue line). In Fig. 4.1, Prob(delay > deadline) denotes probability when delay is bigger than given deadline; P_1 and P_2 denotes red and blue line, respectively. Although P2 has less average delay than P1, due to delay variance, P_1 has less probability of packet delivery within the deadline than P_2 (see Fig. 4.1). Therefore, the routing path with minimum mean delay may not maximize the probability of packet delivery within the deadline. Thus, rather than minimizing mean delay, we focus on minimizing the probability the network delay exceeds the given deadline.

4.2. Deadline-aware Route Selection

D_{queue} is non-deterministic, whereas all other delays, D_{trnas}, D_{prop}, and D_{proc} are deterministic, and is dependent on the router buffer statuses, which depend on network traffic status, i.e., busy or idle. Therefore, this study proposes a routing algorithm focusing on D_{queue}.

We assume the distribution of D_{queue} for a single hop link follows an exponential distribution. This is a reasonable assumption since single hop delay is measured from the backbone network, and D_{queue} has been shown to be at least approximately exponentially distributed over several data sets gathering packets passing a router [14]. It has also been shown that link-level D_{queue} distribution is exponentially distributed [15].

Fig. 4.2 shows example PDFs that sum up 2~4 exponential distribution which has same rate as 10. $D_{end-end}$ also follows long-tailed distribution due to D_{queue} [16]. Like that, although network delay happens randomly during packet delivery, it shows certain distribution.

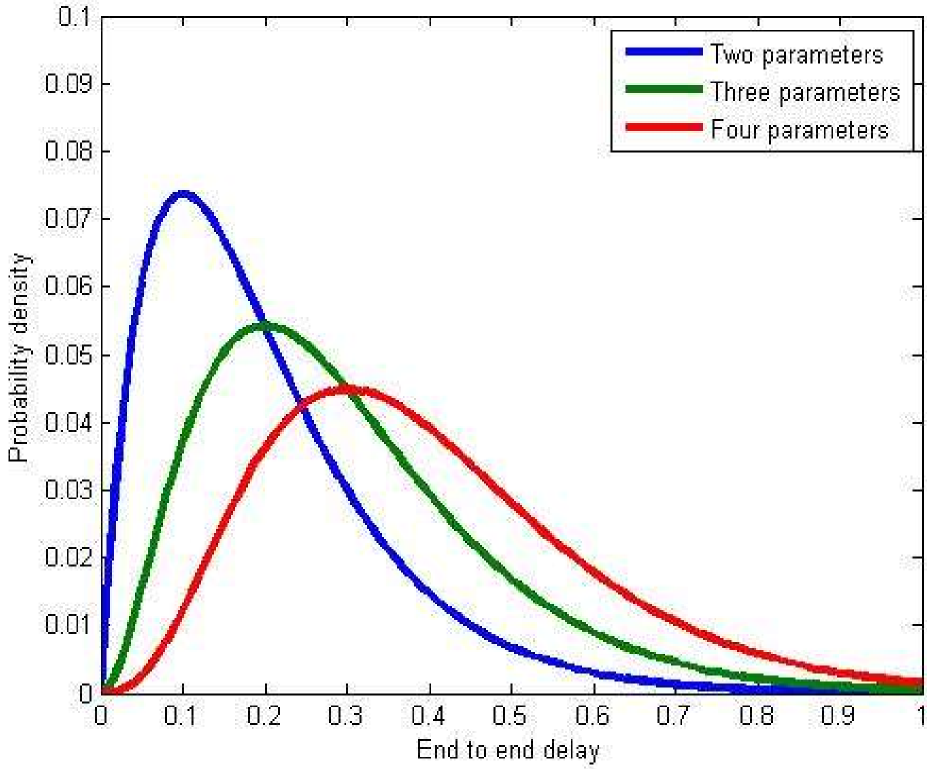


Fig. 4.2. CDF of hypo-exponential distributions:
Each rate of exponential distributions is identical to 10.

Our objective is to guarantee that $D_{end-end}$ is smaller than the given deadline. Delay distribution of each link is summed up to obtain $D_{end-end}$. As mentioned before, exponential distribution is sum up since all delay except D_{queue} is deterministic. Hypo-exponential distribution is a sum of exponential distribution. First, i of each link is exponentially distributed with its own rate of λ_i. Then, the $D_{end-end}$ distribution is expressed as a sum of independent exponential distributions as follows:

$$X = \sum_{i=1}^{n} X_i, \tag{1}$$

where X is the hypo-exponential random variable, and X_i is the exponential random variable for the *i*th link, with rate λ_i. The mean and variance of the end to end path delay in (1) can be expressed as

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

and the probability that $D_{end\text{–}end}$ delay is smaller than the given deadline may be calculated using the hypo-exponential distribution and cumulative distribution function (CDF) as,

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

where λ_i and λ_j denotes rate of link i and link j, respectively. Using the probability calculated from (2), an optimal routing path can be chosen among possible paths from source to destination.

5. SIMULATION AND PERFORMANCE EVALUATION

5.1 Simulation environment

This section evaluates the proposed algorithm performance using MATLAB and Simulink [17]. Fig. 5.1 shows the network topology considered for the simulation, where the number on each link denotes the rate, λ, of the exponential distribution, and the mean delay is $1/\lambda$. Path 1 (Fig. 5.1, red line) and 2 (Fig. 5.1, blue line) denote end to end routing paths from source to destination chosen by deadline-aware and shortest path routing algorithms, respectively.

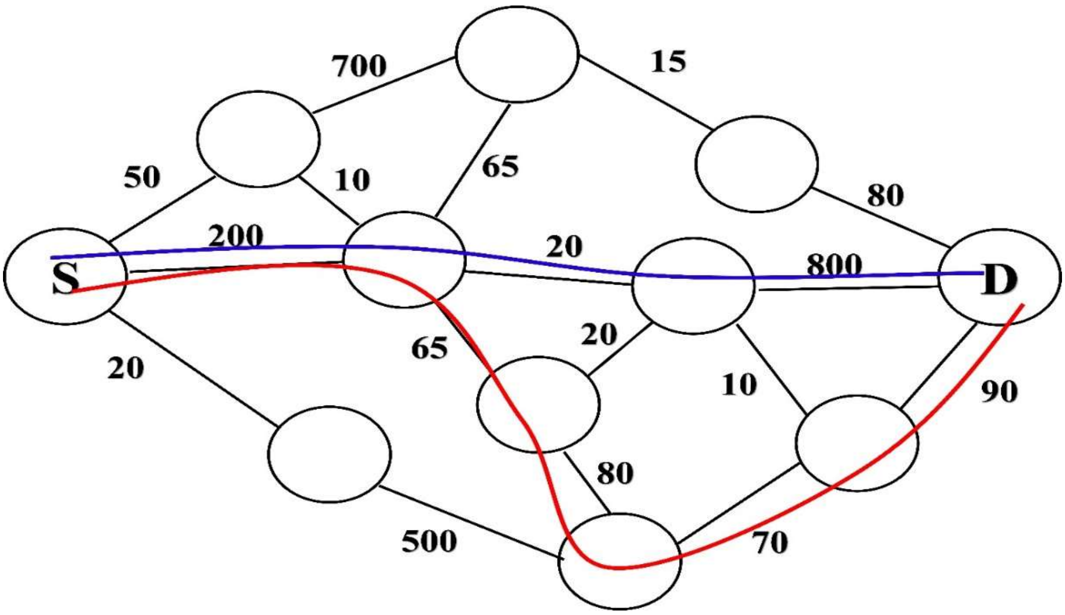


Fig. 5.1. A network topology for performance evaluation. The number on each link denotes the rate $\boldsymbol{\lambda}$ and hence the mean delay of each link is $\mathbf{1}/\boldsymbol{\lambda}$.

Network delay was explained in Section 2.1, and the parameters used in the simulation are described in Table 5.1. All parameters except D_{queue} are assumed to be constant for the convenience of calculation, and to focus on the non-deterministic nature of D_{queue}.

Table 5.1. Delay parameters used in the simulation.

Parameter Type	Value
Distance (D)	1000 meters
Packet Length (N)	128 bytes
Data Bit Rate (R)	10 Mbps
Speed (S)	$3.0*10^8$ m/s
D_{proc}	50 us
D_{trans}	1.024 ms
D_{prop}	3.33 us
D_{queue}	Randomly generated

As discussed above, CPS is a type of NCS that controls physical systems using feedback via the network. Hence, CPS performance is significantly affected by network delay. A typical Simulink model is considered, as shown in Fig. 5.2, incorporating an integrator plant, generally used in industrial applications; and proportional integral controller for system stability, where proportional gain and integral gain were set as shown in Table 5.2, along with the sine wave and constant reference values. The sine wave reference shows how well the system is tracking, and the constant reference is utilized to check maximum overshoot and settling time of the plant. $D_{end-end}$ for each path is added between the controller and plant. Overall NCS delay includes delay from controller to plant, T_{cp}, and from plant to controller, T_{pc}.

Table 5.2. Simulink parameters for simulation.

Sine wave reference	
Amplitude	5
Frequency	5 rad/sec
Constant reference	
Value	10
Controller	
Sampling time	5 ms
Proportional gain	3
Integral gain	1

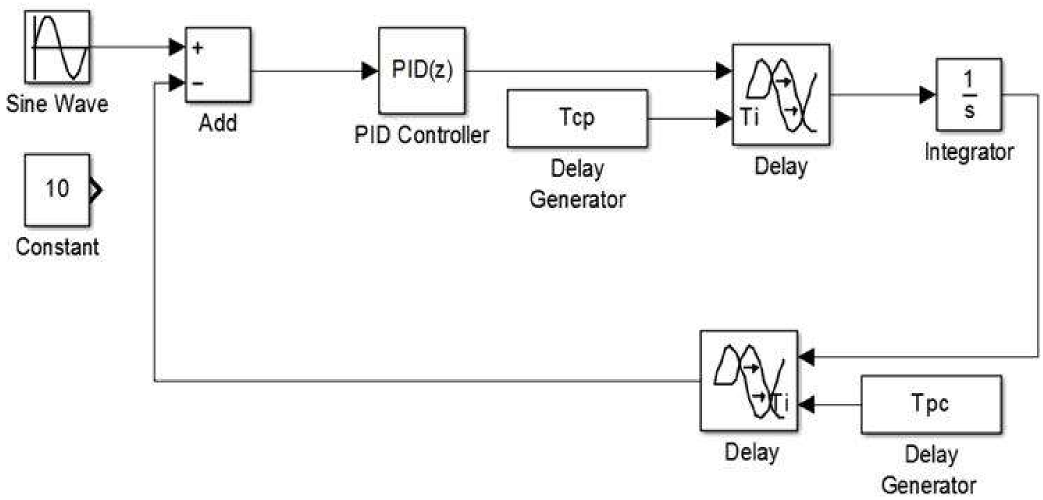


Fig. 5.2. Typical Simulink model of networked control.

5.2. Simulation and Performance Evaluation

We calculated the mean, variance, and CDF for paths 1 and 2 shown in Fig. 5.1 from (1) and (2). The shortest path routing algorithm chose path 2 as the optimal routing path because it had smaller mean delay than path 1, whereas our proposed algorithm chose path 1 as this had higher probability of reaching the destination within the given deadline, even though the mean delay was larger than path 2.

Fig. 5.3 shows the CDF for paths 1 and path 2 defined in Fig. 5.1. The network delay deadline was set at 100 ms. The mean delay of paths 1 and 2 were 58.3 and 56.3 ms, and the probability of arrival within the deadline was 0.9216 and 0.8458, respectively. Although mean delays were similar, the probability of packet arrival within the deadline was significantly influenced by the variance, as shown in Fig. 5.3.

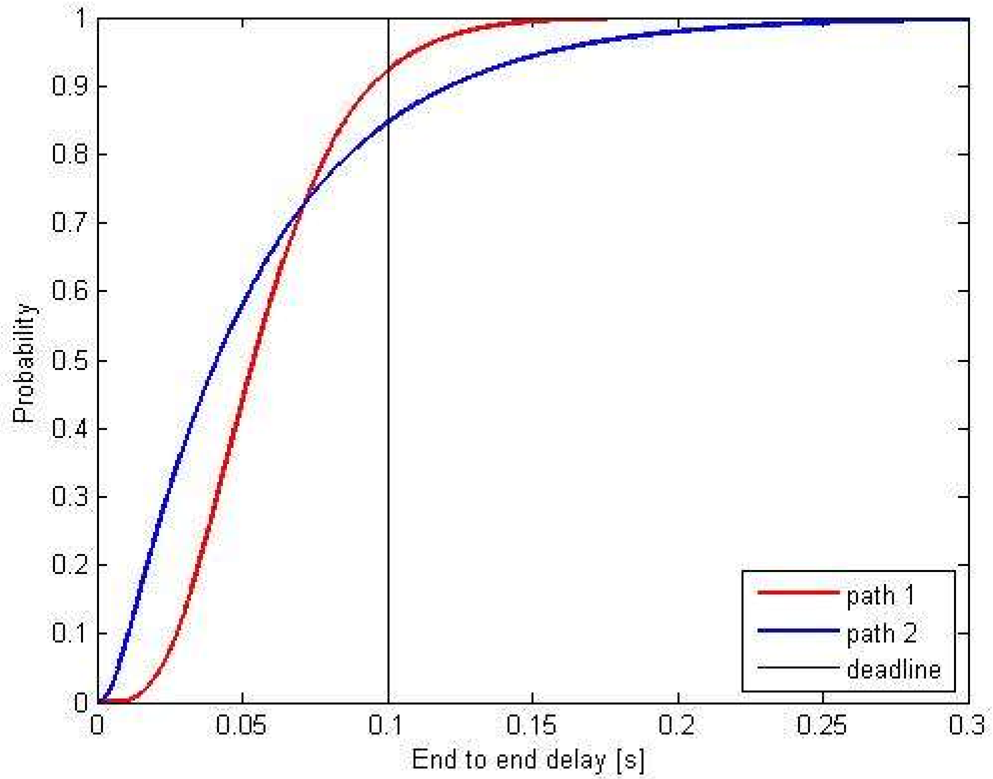
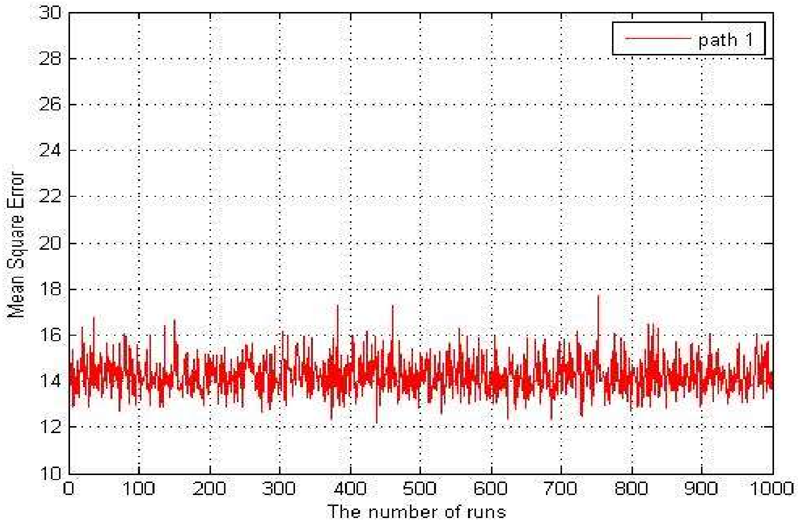
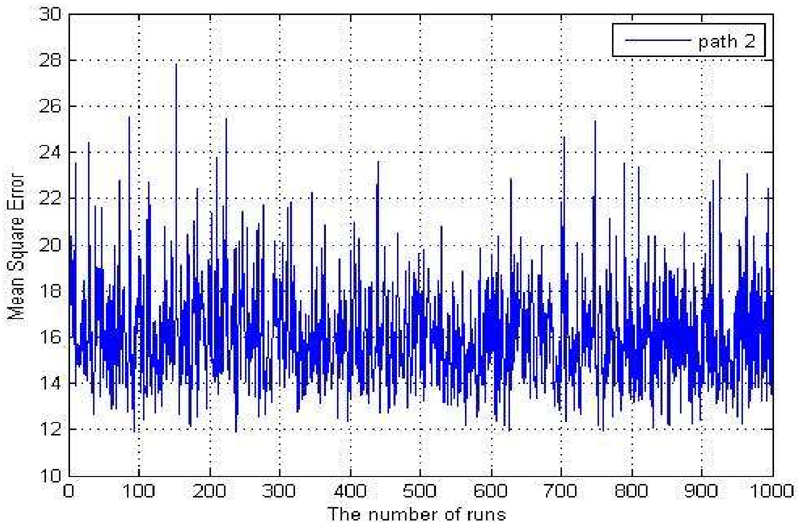


Fig. 5.3. The CDF of path 1 and path 2 from Fig. 5.1.



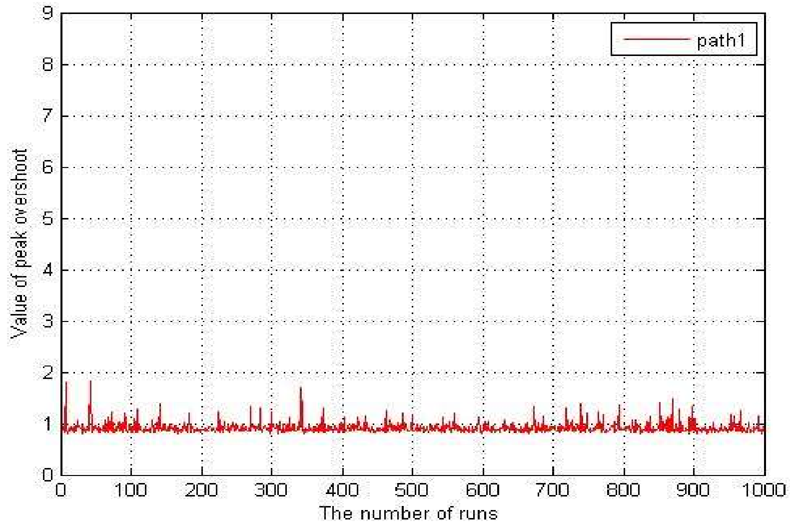
(a) MSE of path 1.



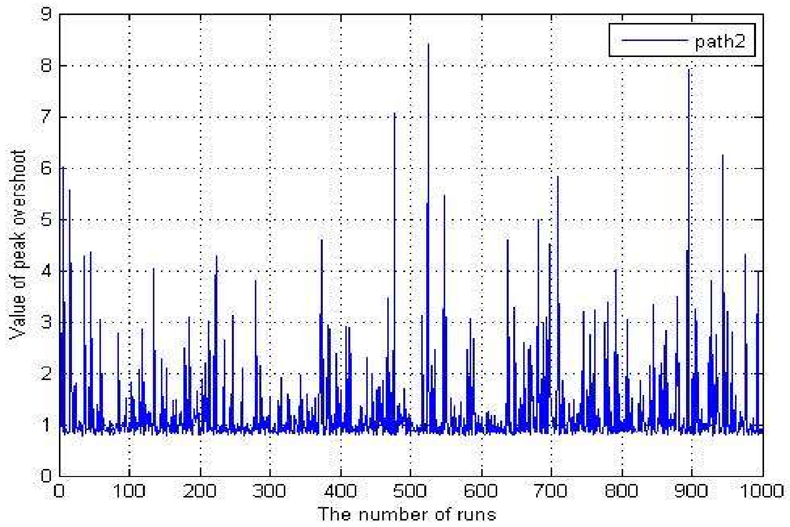
(b) MSE of path 2

Fig. 5.4. The mean square error of networked control with path 1 and path 2.

Figures 5.4(a) and 5.4(b) show the mean square error (MSE) between the sine wave reference and simulated output for paths 1 and 2, respectively. The run-time of the simulation was 20 seconds, repeated 1000 times. The average MSE for paths 1 and 2 were 14.2078 and 16.2528, respectively. Thus, the MSE for path 2 is significantly larger than for path 1, and more irregular.



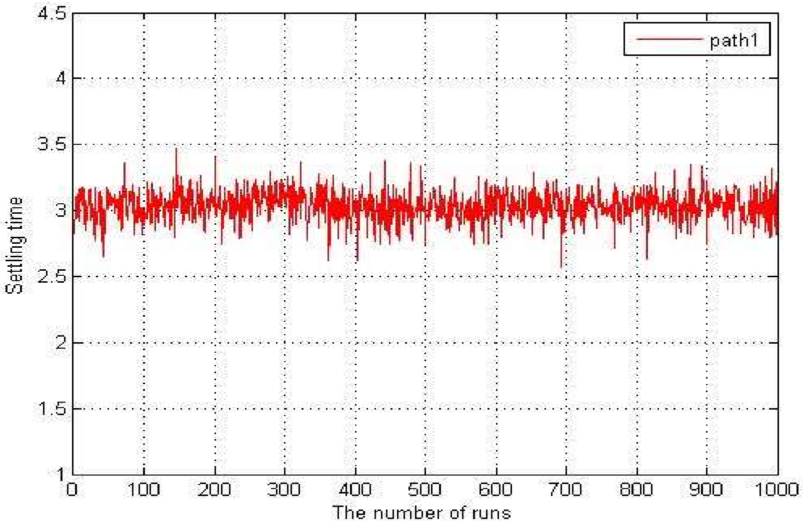
(a) Peak overshoot of path 1.



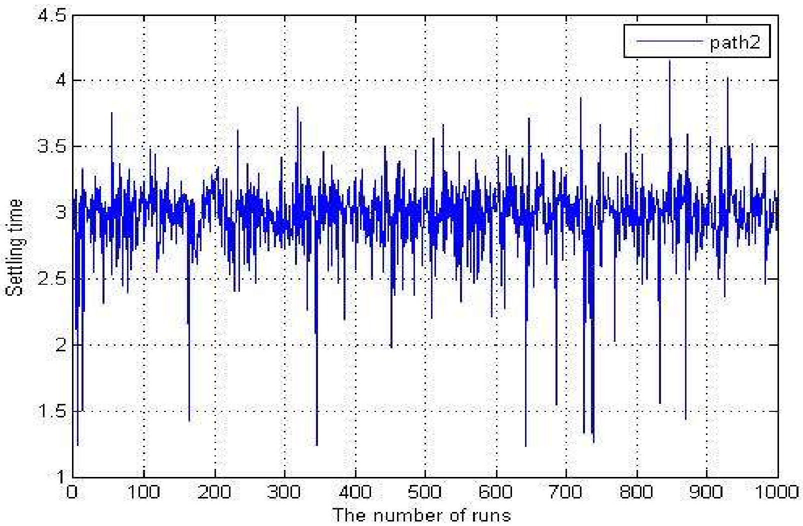
(b) Peak overshoot of path 2.

Fig. 5.5. The peak overshoot of networked control with path 1 and path 2.

Figures 5.5 and 5.6 show the peak overshoot and settling time, respectively, relative to the constant reference for paths 1 and 2. The simulation environment was the same as for Fig. 5.4. Average overshoot for paths 1 and 2 were 0.9020 and 1.2029, respectively. The number of times the end to end delay exceeded the delay threshold (over 1000 runs, and assuming 110% of constant value) for paths 1 and 2 were 89 and 367, respectively; and the peak overshoots were also significantly different (2.1958 and 8.4132, respectively).



(a) Settling time of path 1.



(b) Settling time of path 2.

Fig. 5.6. The settling time of networked control with path 1 and path 2.

Although the average settling times of paths 1 and 2 were 3.037 and 2.987, respectively, and the number of times the delay exceeded the threshold, assuming 110% of the mean value, was 11 and 58, respectively.

The proposed algorithm performance was simulated for several conditions, and MSE, peak overshoot, and settling time are all important factors in assessing control system performance. Control performance was significantly affected by delay variance, and the proposed algorithm showed significantly better control performance compared to conventional shortest path routing algorithm in CPS. Thus, to improve networked control performance, not only the mean network delay, but also the variance must be considered, and the optimal routing pathway should be derived using a stochastic algorithm, as per that proposed.

6. CONCLUSION

We proposed a deadline-aware routing algorithm to satisfy a probabilistic delay constraint in CPS. The objective of the proposed routing algorithm was to maximize the probability of packet arrival within a given deadline. Since CPS requires timely packet delivery for QoS, the probability of packet arrival within the deadline is a critical factor. We satisfied the system requirements by considering the mean and variance of the overall delay, $D_{end-end}$. Simulation result showed that the proposed algorithm significantly improved networked control performance, measured by MSE, as well as system stability, measured by peak overshoot and settling time, compared with the conventional shortest path routing algorithm.

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요 약 문

사이버-물리 시스템의 서비스 품질 향상을 위한 데드라인 인지 라우팅 알고리즘

본 논문에서는 사이버-물리 시스템의 서비스 품질 향상을 위해 시스템의 데드라인을 고려한 라우팅 알고리즘을 제안한다. 보편적으로, 대부분의 라우팅 알고리즘은 평균 딜레이를 라우팅 메트릭으로 하여 이를 최소화 하고 평균 성능 향상을 목적으로 한다. 하지만, 사이버-물리 시스템과 같이 데드라인에 민감한 시스템들은 패킷에 대한 적절한 전송시간을 요구하기 때문에, 평균 딜레이는 라우팅 메트릭으로써 적합하지 않다. 제안한 알고리즘은 평균 딜레이가 아니라, 딜레이의 평균과 분산에 따른 분포를 고려함으로써 시스템의 정해진 데드라인 이내에 도착할 확률을 최대화 하는 것을 목적으로 한다. 이에 따라, 제안한 알고리즘은 사이버-물리 시스템에서 네트워크를 기반으로 하는 제어 시스템의 서비스 품질을 향상 시킬 수 있다. 우리는 제안한 알고리즘의 성능을 평가하기 위하여, 링크 딜레이가 지수 분포를 따른다는 가정을 한다. 그리고, 문제의 네트워크 토폴로지와 시뮬링크 상에서 제어 시스템을 구성하고 여러 가지 상황에 따라 시뮬레이션을 수행 하였다. 그 결과, 제안한 알고리즘이 사이버-물리 시스템에서 최단 경로 알고리즘에 비해 데드라인을 더 효과적으로 만족하였고 또한 제어 성능의 상당한 향상을 보였다.

핵심어: Routing algorithm, Cyber-physical systems, network delay, variance, control performance