Adaptive Selection of Multiple Paths for Delay-Sensitive Networked Control Systems

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***Abstract*—In real-time networked control systems, the end-to-end path delays on the communication network should be bounded in order to satisfy the stringent timing constraints of physical system. While the packet delivery on a single path could be significantly affected by network congestion levels, transmitting duplicate packets along multiple paths can overcome fluctuations of the time delay on a specific path by exploiting the diversity of multiple paths. As such, we propose a multi-path selection scheme that selects an appropriate number of multiple paths while minimizing the network traffic overhead due to multiple paths.**

***Index Terms*—networked control system; real-time network; path diversity**

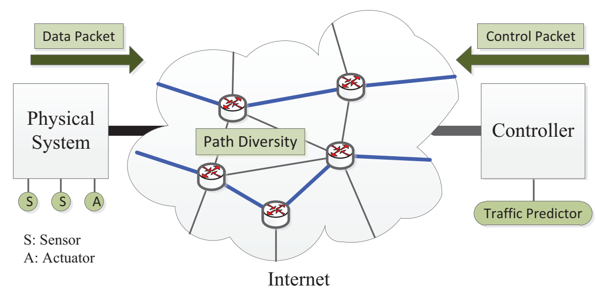

Fig. 1. System model of networked control systems

I. Introduction

A networked control system (NCS) is typically composed of physical systems, control/computation components, and communication systems that connect them through wired and/or wireless communication networks. If each component is independently designed and abstracted without sufficient consideration of the other components, the NCS may not operate properly or become easily unstable when all the components are incorporated together. In the case that the components, including all communication and computing processes, could not provide predictable and reliable services to a system that requires a high quality of services (QoS), it would be dangerous if such a physical system is designed based on the misbelief that the communication is perfectly reliable.

In this paper, we consider the networked control of real-time physical systems via the Internet. The Internet was originally only designed to provide a "best effort" service, which does not guarantee QoS such as in-order packet delivery, reliable data delivery without loss, bounded latency and jitter, and so on. To mitigate this weakness, a number of techniques have been proposed to improve and guarantee the QoS on the Internet, many of which have focused on priority scheduling—though this requires additional network system modifications [1], [2]. Several methods for exploiting path diversity methods also have been studied [3]–[5], but most have tried to utilize path diversity in order to enhance the end-to-end throughput performance by balancing the traffic load among multiple paths rather than the end-to-end latency performance.

Here, we propose a multi-path selection scheme that selects the proper number of multiple paths such that the end-to-end delay can be kept lower than the delay constraint required by the physical system. The proposed scheme first identifies the path characteristics using probing packets, and then selects the minimum number of multiple paths with which the delay constraint of the physical system can be satisfied.

II. Model description

We consider an NCS in which the controller communicates with the physical system via the Internet, as shown in Fig. 1. In this case, the packet delivery time between the controller and physical system should be bounded by a certain value in order to make the physical system stable. In this paper, we simply assume that the timing constraint is given as τ_c in advance.

The physical system measures the current status and sends it to the controller at every τ_s, as shown in Fig. 2, as a client in network service model. The remote controller then responds to the physical system by sending the corresponding control packet, as a server. The figure clearly shows these interactions between the physical system and the remote controller. The round trip time (RTT) is the time interval between the instants when a data packet is sent and when the corresponding control packet is received at the physical system. Let τ denote the RTT measured from the physical system; then, it is required that $\tau < \tau_c$ in order to make the physical system operate in a stable manner. However, because the network delay is not deterministic, we represent the delay requirement as follows:

$$\text{Prob}[\tau > \tau_c] < \epsilon, \quad (1)$$

where ϵ is a small constant.

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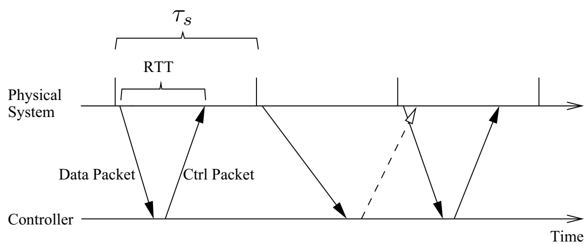

Fig. 2. Interaction between the physical system and controller.

We also assume that there are a sufficient number of disjoint paths available (Fig. 1). To maximize multiple path diversities, each path should be disjointed; otherwise, duplicate packets from the physical system to the controller may cause significant path congestion.

III. Multiple Path Selection

In order to exploit the path diversity, we propose a "simultaneous duplicate transmission", which sends duplicate packets through multiple paths. The physical system simultaneously sends duplicate data packets to the controller through N multiple paths at every τ_s. When the controller receives the data packets, it computes the proper control output value for the physical system, and then sends the duplicate control packets via the multiple paths. Thanks to the simultaneous transmissions, the effective RTT experienced by the physical system is given by the minimum value among the RTTs of the multiple N paths, such that

$$RTT_{min} := \min(RTT_1, \cdots, RTT_N). \quad (2)$$

By (2), the delay constraint can be rewritten as

$$\text{Prob}[RTT_{min} > \tau_c] < \epsilon. \quad (3)$$

If we let f_{RTT_i} denote the probability density function (PDF) of RTT_i, then the cumulative density function (CDF) of RTT_{min} is derived as follows:

$$F_{RTT_{min}}(x) = 1 - \prod_{i=1}^{N}(1 - F_{RTT_i}(x)).$$

In this case, the PDF of RTT_{min} is given by

$$f_{RTT_{min}}(x) = \sum_{i=1}^{N} f_{RTT_i}(x) \prod_{n=1, n\neq i}^{N} (1 - F_{RTT_i}(x)).$$

It can then be shown that the simultaneous transmissions along multiple paths can achieve a lower end-to-end latency of packet delivery as the number of multiple paths increases.

A. Appropriate Number of Multiple Paths

Because these simultaneous transmissions may incur a significant overhead in network bandwidth resources, it is critical to find a smallest set of multiple paths that satisfy the delay constraint. Indeed, the goal of our multi-path selection algorithm is to determine the appropriate number of multiple paths with which the end-to-end delay can be kept lower than the delay constraints in (3). Note that the routing algorithm that finds disjoint multiple paths is out of scope of this paper.

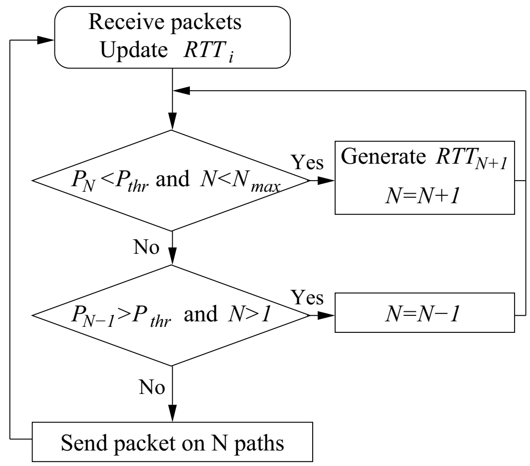

Fig. 3. Procedures of the proposed multiple path selection algorithm where N_{max} is the maximum number of available paths.

To select the appropriate number of multiple paths, we start with a small number of candidate multiple paths. Then, among the selected N paths, M probing packets are sent, and RTTs are measured. Note that if there is any traffic on the selected paths, the passive measurement of RTTs using existing traffic flows is also possible. From the RTT measurements, a decision as to whether or not the selected paths can satisfy the delay constraint of (3) is made. To expedite this decision process, we use the following method. First, we introduce a binary variable δ_{ij} for the RTT measurement of the jth probing packet on the ith path:

$$\delta_{i,j} := \begin{cases} 1, & \text{if } RTT_{i,j} < \tau_c \\ 0, & \text{otherwise,} \end{cases}$$

where RTT_{ij} is the RTT measurement for the jth probing packet on the ith path. Then, we also define F_j^N for the RTT measurements from jth probing packets sent along all N paths as follows:

$$F_j^N := \begin{cases} 1, & \text{if } \sum_{i=1}^{N} \delta_{i,j} \neq 0 \\ 0, & \text{otherwise.} \end{cases} \quad (4)$$

Note that for the jth probing packet, $F_j^N = 1$ if $RTT_{min} < \tau_c$; otherwise, $F_j^N = 0$. Finally, the delay constraint of (3) can be rewritten as

$$P_N := \frac{1}{M} \sum_{j=1}^{M} F_j^N > P_{thr}, \quad (5)$$

where $P_{thr} = 1 - \epsilon$.

B. Adaptive Prediction Algorithm

The detailed procedures of our proposed multiple path selection scheme are shown in Fig. 3. Here, the most important operation is how to predict whether or not the newly selected set of $(N-1)$ multiple paths satisfies the delay constraint

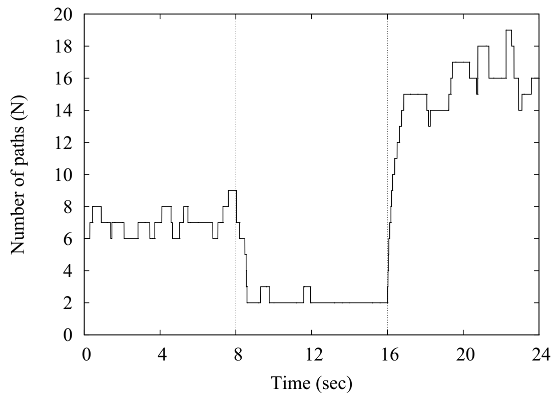

Fig. 4. Adaptation of the number of multiple paths with respect to the time elapsed.

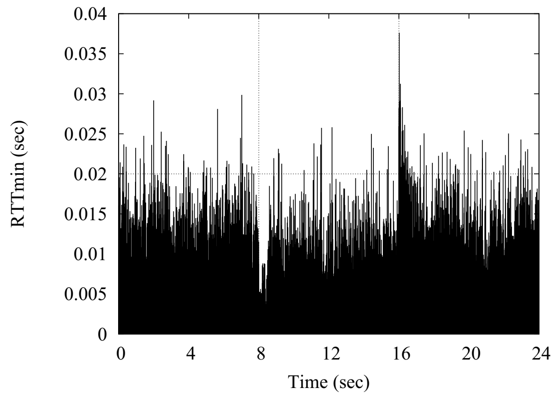

Fig. 5. Variation of RTT_{min} with respect to the time elapsed.

when the worst path with the longest RTT is excluded. This can be tested by the following inequality:

$$P_{N-1} = \frac{1}{M}\sum_{j=1}^{M} F_j^{N-1} > P_{thr}, \quad (6)$$

where F_j^{N-1} is the binary variable in (4) for the $(N-1)$ multiple paths. If the inequality of (6) is satisfied and $N > 1$, we can decrease the number of paths by discarding the worst path.

In contrast, if the inequality of (5) is not satisfied and $N < N_{max}$, we increase the number of paths N by one. Here, N_{max} is the maximum number of available multiple paths on the network. Within the loop of the algorithm in Fig. 3, we generate a synthetic RTT measurement for a new path to be added from that of the worst path L, without making an actual measurement.

$$RTT_{N+1} = \text{randperm}(RTT_L), \quad (7)$$

where randperm$(\cdot)$ is a function that randomly permutates the sequence of an input vector.

IV. Simulation Results

We evaluated the performance of the proposed multi-path selection scheme in an NCS in which $\tau_c = 0.02$ and $\epsilon = 0.01$. Since the performance of the proposed scheme highly depends on the RTT characteristics, we dynamically vary the the RTT; initially, the RTTs on the paths are moderate for 4 seconds, and then they rapidly decrease and is kept low for another 4 seconds. After that, the network is heavily congested and thus the RTT significantly increases. The system parameters are set as $N_{max} = 30$ and $M = 300$.

Fig. 4 shows the number of selected multiple paths (N) with respect to the simulation time. For the first 4 seconds, the proposed scheme selects 7 multiple paths. When the network is not congested at all for the next 4 seconds, the RTT delay is seen to have dropped considerably, and the proposed scheme subsequently reduces the number of paths. We also observe that the proposed multi-path selection scheme maintains the $P[RTT_{min} < \tau_c] \approx P_{thr}$ value while minimizing the network traffic overhead in Fig. 5. When the network becomes heavily congested from 16 to 24 seconds, the selected number of paths accordingly changes, while most RTT_{min} are kept below τ_c.

V. Conclusion

We considered an NCS in which the delay of the end-to-end path on the communication network should be bounded in order to satisfy the stringent timing constraints of a physical system. We proposed a multiple path selection scheme that adjusts the number of multiple paths that can satisfy the timing constraint while minimizing the network traffic overhead incurred due to multiple paths. Through various simulations, we demonstrated that the proposed scheme meets the requirements for controlling the delay-sensitive physical system. As future work, we will construct a real test-bed capable of controlling a linear-inverted pendulum via the Internet.

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