Work-in-Progress: Cross-layer Real-Time Scheduling for Wireless Control System

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***Abstract*—Wireless control systems are gaining a lot of attention, due to its easy deployment comparing to wired control systems recently. Real-time wireless networks have been proposed to give preference to high-priority tasks and keep timeliness of packet delivery. In control systems, however, network delay influences significantly the control system performance, whose applications have dynamic characteristics. Motivated by the observation, we propose a dynamic network scheduling solution to minimize the error in control applications in a system, by considering the application behavior and changing its priority based on dynamic conditions. We plan to conduct a case study based on a nuclear power plant to analyze the interaction between cross-layer real-time network scheduling and control.**

***Index Terms*—wireless control system, real-time scheduling, cross-layer, cyber-physical system**

I. Introduction

Wireless control systems (WCS) comprise controllers, sensors, relay nodes, and actuators connected via a wireless network. WCNs operating over multi-hop wireless (sensor) networks have received significant attention in recent years [5], [8], [9], [12], due to the ease of deployment. However, the network-induced imperfections, such as network delay and packet losses will degrade the control system performance. When multiple control systems utilize one shared wireless network, the network imperfections will impact each control system differently, depending on the control systems application demands.

We implemented a wireless control system for a nonlinear primary heat exchanger system in a nuclear power plant (NPP). The system is a Simulink implementation of the NPP, which contains control code, sensor inputs, and actuator outputs; the control code takes into account several parameters as described below. The primary heat exchanger subsystem (PHX) in the NPP has its main function as the exchange of heat from inside of the reactor to the outside, which controls the pressure and the temperature of the reactor. The PHX is typically modeled as a nonlinear system and there is typically one PHX and 2 secondary ones in each nuclear reactor. Each PHX has three measurements that are sent periodically to the controller, namely outlet hot leg temperature, inlet hot leg temperature, and mass flow rate via wireless network.

A new wave of NPPs consider several Small Modular Reactors (SMRs) [4], instead of a single large reactor, due to the flexibility and cost-benefit of starting and stopping SMRs. Figure 1 shows an NPP with three PHXs (three SMRs and 6 secondary heat exchangers), each of which transmits measurement data via a shared wireless network (in total maximum 9 measurements sending periodically). Given that there are several SMRs in an NPP, the power output of each SMR may differ and the controller may decide to change the power output of each SMR dynamically, based on energy requirements and balancing the power required to achieve a certain level of power output. Figure 2 shows 8 different ideal scenarios (each is associated with a *power reference function*) of a PHX when the controller decides to reduce the output power from 42MW to 32MW. In the X-axis, we show the sample time (note that the control system sample period is 0.1s, sample time means current time / 0.1) and in the Y-axis we show the desired level of power output required. For example, ramp30 is supposed to reduce the power from 42MW to 32MW within 30s. As mentioned above, for real-world applications in NPPs, different PHX may have different power demand, which means they may have different reference functions; how they vary is beyond the scope of this paper (we assume ramp for now).

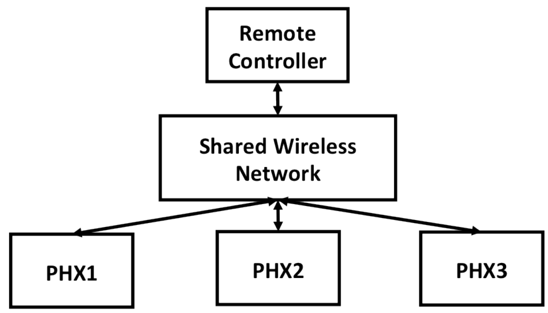

Figure 1: System overview: three PHXs transmit measurements via shared wireless network to the remote controller

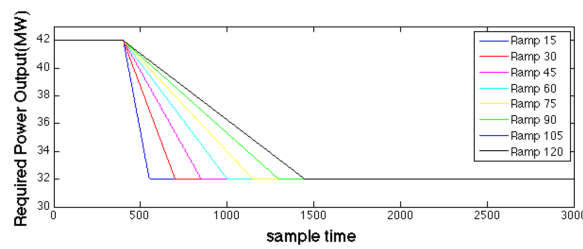

Figure 2: Control system power reference functions

In Figure 3 we show the effect of network delays and power

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reference functions on a single PHX system. We measure system performance via power RMSE (Root Mean Square Error of the power output)[1]. We also varied the delivery ratio (DR, which is the percentage of the messages that arrive at the controller) and show DR=0.9, while other values of DR show similar characteristics of the RMSE. We also measured the IAE (integral absolute error) and MAE (maximum absolute error); results can be found in Figures 5 and 4). Figure 6 shows the power output RMSE for different network delays and delivery ratios when the reference function is ramp30 (similar results for the other reference functions). We have three observations:

(1) From Figure 3, 4 and 5, for the same network delay and DR, the steeper the reference function, the larger the RMSE. This is because when the reference function is steep, it requires the control system to reduce its power output aggressively (in much less time), and thus it will have the more transient response, causing larger RMSE. However, after 60 seconds (i.e., ramp60), the control system performs similarly.

(2) From Figure 3, 4 and 5, for the same reference function, the higher the network delay, the larger the RMSE. For the steeper reference functions, the network delay becomes a more significant factor on the control system performance. For example, the control system performance of ramp15 with delay=0.2s is the same as the performance of ramp45 with delay=0.4s.

(3) From Figure 6, we observe that the system is delay-sensitive system. The packet losses effect can be ignored when the DR is greater or equal to 0.7, comparing to the delay effect.

Motivated by the above three observations, for delay-sensitive system, we will set a smaller network delay (aka deadline) for the more urgent application demand (e.g., ramp15, or more aggressive output changes) and a more laxed deadline for the less urgent applications (e.g., ramp45). We plan to achieve that by dynamically scheduling the network flows, based on the application layer demand. We call this kind of dynamic scheduling *cross-layer real-time scheduling*, given that it takes application behavior into account and changes deadlines to influence packet scheduling at the network layer.

Our objective function can be seen in Equation 1, where n is the total number of physical systems controlled over one wireless network, in which each physical system has its own reference function, depending on its application demand.

$$obj = min \sum_{i=1}^{n} RMSE_i \quad (1)$$

In this paper, we focus on cross-layer real-time scheduling for the delay-sensitive control systems, to maximize the overall control system performance (minimizing the RMSE of all the control systems), when multiple control systems share one wireless network to do data transmission. We will propose a cross-layer real-time scheduling strategy. To see the interaction

[1]The metric measures the RMS error between the closed-loop responses using wired control (i.e., we assume there are no packet drops and no network delay in wired control) and wireless control.

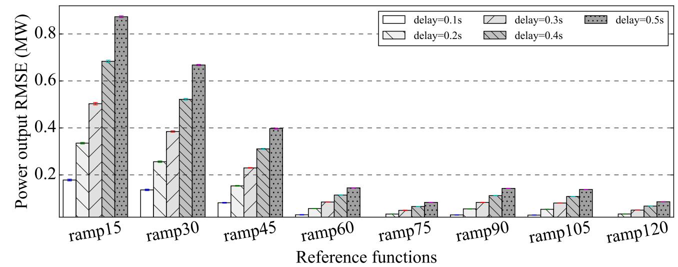

Figure 3: Power output RMSE for different reference functions with different network delay for a single PHX (DR=0.9 with random packet drop)

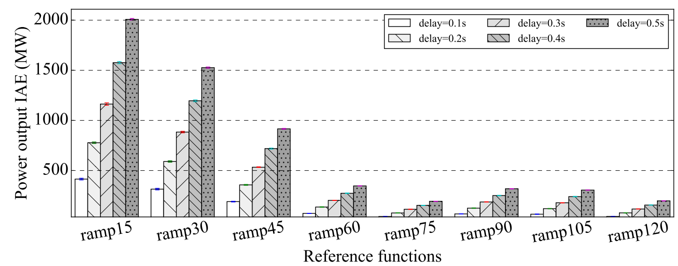

Figure 4: Power output IAE for different reference functions with different network delay for a single PHX (DR=0.9 with random packet drop)

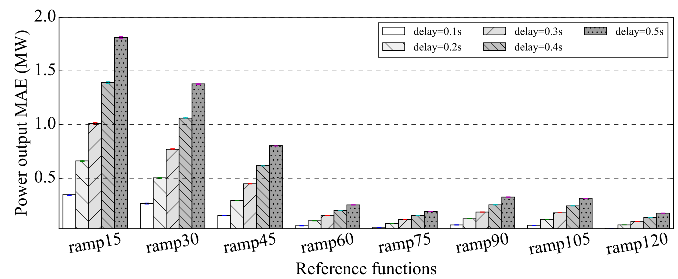

Figure 5: Power output MAE for different reference functions with different network delay for a single PHX (DR=0.9 with random packet drop)

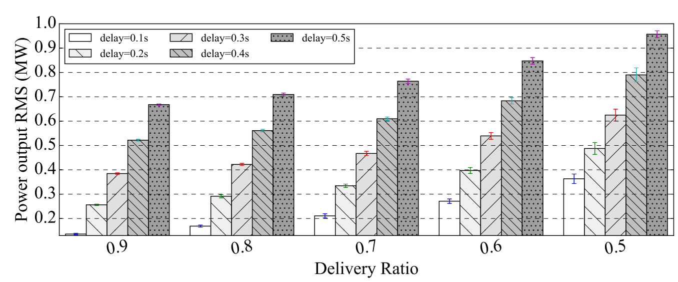

Figure 6: Power output RMSE for different reference functions with different network delay and delivery ratio for a single PHX (reference function: ramp30)

between dynamic network scheduling and the control, we plan to conduct a systematic case study on three heat exchangers in a NPP controlled over one shared multi-hop wireless network.

II. Related Work

Cross-layer network scheduling is an effective solution, which has been studied in many research works. The cross-layer network scheduling is explored in [8] with slot stealing algorithm [3] to reserve time slots for emergency packets. Although a systematic case study is conducted for a water tank system, neither control system performance maximization is considered, nor multiple control systems are involved. Online data link layer scheduling is studied based on a rhythmic task model [7] in [6]. While the impact of network dynamics on existing network flows is minimized, overall control system performance is not considered and there is no case study for real-world applications. In [2], the author derives a sufficient condition for the random access communication policy of shared wireless medium and design a control-aware random access communication policy. However, the authors do not consider the demand of application layer. Finally, a popular cross-layer optimization is the one for multimedia systems, where videos and large files have to abide by a certain QoS (quality of service) [11], [13], [1], which is different from our approach of small data packets over small multi-hop sensor and relay nodes.

III. Problem Formulation and Intuitive Solution

Similar to [10], we define a set of N end-to-end network flows as $F = \{F_1, F_2, ..., F_N\}$. Each network flow delivers one measurement to the remote controller. Each flow F_i associated with a source s_i, a destination d_i, a period p_i, a deadline D_i and a current reference function ramp ratio r_i. The deadline D_i is defined as

$$D_i = D_{steady} * (1 - \alpha \times r_i) \quad (2)$$

where α is a constant and D_{steady} is the deadline to guarantee the system stability [12].

The network flow set is divided into two subsets, critical flow set and non-critical flow set. In our case (see Figure 3), the flows with ramp time greater than 60s are critical flows. For each flow in non-critical flow set, the ramp ratio r_i is 0 and $D_i = D_{steady}$. In other words, we treat all the non-critical flows the same. The priority of each flow is ordered by its deadline. Earliest deadline has the highest priority. Our intuitive algorithm is as follows. The remote controller will decide the priority for each network flow F_i and send the priority information to the PHXs in SMRs. The network flow priority information is attached to each message. Every node in the network will order the received messages by the network flow priority/deadlines, and send the message with highest priority first. The algorithm complexity is $O(n \log n)$.

IV. Conclusion

We explore the interaction between dynamic network flow scheduling and the control. For the delay-sensitive control system, we observe that network delay plays the major effect on control system performance when the application demand is urgent. We propose an intuitive cross-layer real-time scheduling algorithm to gain more control performance, by setting tight deadline for network flows with urgent application demand.

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