Performance Composition for Cyber Physical Systems

Shan Lin
Department of Computer Science
University of Virginia
shanlin@cs.virginia.edu

John A. Stankovic
Department of Computer Science
University of Virginia
stankovic@cs.virginia.edu

***Abstract*—Extensive studies have shown that cross-layer wireless networking design and optimization can gain significant performance improvements for cyber physical systems. Because this optimization problem is NP-hard, most previous solutions develop heuristics based on mathematical abstractions. In highly dynamic networks, such models may not be accurate or efficient. To address this problem, we explore a hierarchical control approach to optimize the performance of the system. In this design, a network controller adjusts the performance requirements for links at different control rates, while every node has a controller that takes the performance requirements as input and adaptively adjusts parameters of network protocols cross-layer. This design is based on a reflective architecture that we propose to treat control as a first class element in CPS system designs, enabling component performance analysis for CPS. Our solution can potentially achieve good control performance: stable network performance and good transient performance.**

I. Introduction

A large number of emerging cyber physical systems applications, such as scientific exploration, military surveillance, and medical care systems, require high quality of performance to collect accurate data traces or deliver urgent data reports. These application-specific performance requirements are important design goals of such systems. The general performance requirements include timeliness, system lifetime, and reliability. To meet these requirements on platforms of extremely limited resource, it is often necessary to jointly optimize and design network protocols.

Extensive cross-layer research has been done for wireless sensing systems, wireless ad-hoc networks, and other wireless embedded systems. As a general methodology, performance requirements are translated to requirements of representing metrics at different layers, for example, bit error rate at the physical layer. To meet these layered requirements, the system allocates resources to each layer and optimizes the performance. These works provide valuable results and good performance in relatively static systems, as these solutions require accurate models and estimations of parameters. However, in highly dynamic systems, the performance of these solutions may not be satisfactory due to inaccurate estimations and overhead. To address this problem, it is essential to adjust system parameters adaptively to optimize the runtime performance in dynamic systems. As control theory provides a sound foundation to monitor system performance and adaptively take actions to influence the performance, we believe that employing a feedback control approach is a key principle for the CPS design.

We explore control based design for wireless networking in CPS systems. To utilize control knobs of different subsystems and layers, we propose a reflective architecture that treats control as a first class element for system design. This design provides a generic two-way interface for information exchange cross-layer and cross-node. Our architecture design abstracts the essence of control modularity so that control modules fit in the traditional layered system design without extra overhead. We design a hierarchical control framework for cross-layer CPS design in the reflection architecture. We consider a scenario of multiple source nodes and multiple destination nodes. The network control on a destination node monitors the network performances of each data stream to this node, and adjusts performance requirements for nodes that forward data. The local control on every node takes performance requirements per stream as input and adaptively adjusts parameters of network protocols cross-layer. This framework adaptively adjusts network parameters cross-layer and cross-node to meet application performance requirements. Moreover, this design obtains control performances in terms of stability and transient performances. Previous solutions that are based on heuristics do not have these properties.

II. Cyber Physical System Composition

The dynamics found in the physical world affects the system performance, especially wireless networking performance. To address this problem, we must design wireless networking protocols to bridge the gap between dynamic communication quality at physical layer of each node and the application performance requirements of the overall network.

Figure 1 shows the vertical and horizontal constraints for CPS design. In Figure 1 (a), we can see that cyber physical

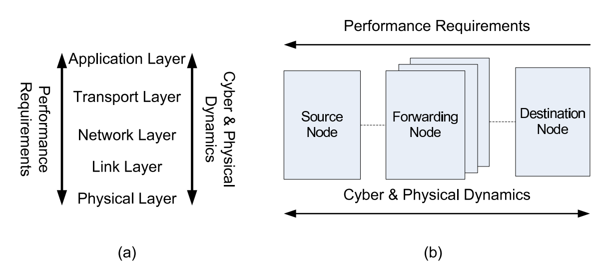

Fig. 1. Cyber Physical System Design Constraints

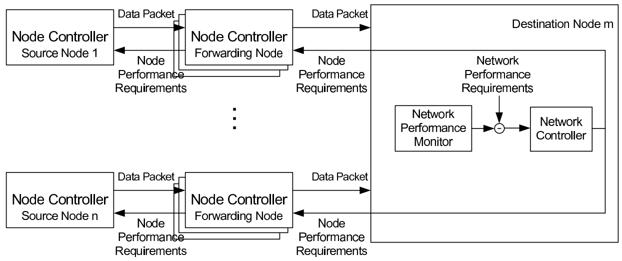

Fig. 2. Network Composition

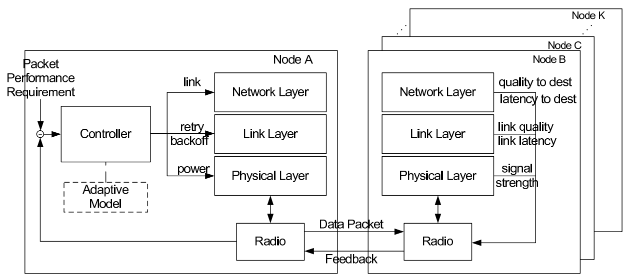

Fig. 3. Node Composition

dynamics impose bottom-up constraints while application requirements impose top-down constraints. In Figure 1 (b), cyber physical dynamics and application requirements also affect the cooperation across nodes. The local performance variations directly lead to changes of the global performance in multi-hop networked systems, since the end-to-end performance consists of hop-by-hop performance of each node. To better address these challenges, it is essential to utilize two-way information exchange cross-layer and cross-node for CPS designs.

A. *Reflective Architecture*

We believe that by considering these vertical and horizontal constraints, system performance can be optimized. This requires components to tightly cooperate with each other. The traditional encapsulated component design approach hides dependencies, which does not provide enough support for optimization. In order to achieve better performance, components need to expose the necessary internal information and take optimization actions. We propose a reflective architecture as a unifying mechanism for information exchange cross-layer and cross-node, supporting both traditional designs and control solutions.

The reflective architecture provides abstractions of reflective information and control. A class of reflective information is critical. This information includes sensing data, performance measurements, timing, and resource availability. On the other hand, a class of control parameters is also vital. The control parameters refer to adjustable configurations, including standard network protocol configuration parameters and specially designed control knobs.

Traditional interfaces mainly focus on providing functionality, while hiding the dependencies and requirements among components. We define reflective interfaces as the interfaces that provide dependency relevant and requirement relevant functionality. In addition, the reflective interfaces make generic management of the coupled components possible without breaking the rule of information hiding [1].

Reflective information is not new in system design [2][3], however, utilizing a reflective interface as a key for multi-dimensional optimization for control solutions in wireless sensor networks is new. The reflective architecture enriches the design space and allows control-based performance analysis among components.

B. *Control Design*

Control theory is one of the key technologies to guide wireless communication designs for two important reasons: first, feedback control theory is renowned for its robustness and stability for dynamic systems; second, feedback control introduces control performances, such as transient performance, which are desirable for CPS designs; third, feedback control introduces sound analysis for system composition.

Our design goal is to meet application performance requirements while efficiently dealing with cyber physical dynamics. Typical performance requirements are timeliness, reliability, and energy consumption. We represent these requirements as performance measures in terms of delay, packet delivery ratio, and energy cost.

As shown in Figure 2, network performance monitors and controllers are located on the destination nodes while node controllers are located on source nodes and forwarding nodes of the network. The network performance monitor measures the end-to-end performance of each data stream and compares them with specified application requirements, the errors are input to the network performance monitor. The network performance monitor calculates and outputs desired node performance requirements according to current performance errors, costs, and optimization goals. The node performance requirements are then fed back to relevant nodes along the routing path.

On each node, we consider a number of critical networking parameters for modeling and control: the transmission power on the physical layer, the backoff time and the number of retransmissions on the link layer, and the choice of forwarding links on the network layer. The monitored performance measures include the received signal strength at the physical layer, the packet reception ratio and delay at the link layer, and the reception ratio and delay to destination at the network layer.

As shown in Figure 3, the node controller takes the error between node performance requirement and monitored performance as input, and calculates configurations of network protocols. The adaptive models of the node control are also updated.

References

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