xTune: Online Verifiable Cross-Layer Adaptation for Distributed Real-Time Embedded Systems

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Abstract

Adaptive resource management is critical to ensuring the quality of real-time multimedia communication, particularly for energy-constrained mobile handheld devices. In this context, a holistic cross-layer optimization considering multiple layers (e.g., application, middleware, operating system) needs to be developed for continuous adaptation of system parameters. This thesis proposes a unified framework that employs iterative policy/parameter tuning by combining light-weight, on-the-fly formal verification with feedback for dynamic adaptation. The integration of formal analysis with dynamic behavior from system execution will result in a feedback loop that enables model refinement and further optimization of policies and parameters. Our unified framework tunes the parameters in a compositional manner allowing coordinated interaction among sub-layer optimizers that enables holistic cross-layer optimization.

1 Introduction

Next generation mobile embedded applications are highly networked, and involve end-to-end interactions among multiple layers (application, middleware, network, OS, hardware architecture) in a distributed real-time environment. The dual goals of ensuring adequate application QoS (Quality of Service, expressed as timeliness, reliability, and accuracy) and optimizing resource utilization at all levels of the system presents significant challenges. As we see from the layered view of a device in Figure 1, policy selection determines how decisions are made at different layers: a specific video encoding/decoding algorithm at the application layer [9]; network monitoring at the middleware layer; and DVS (Dynamic Voltage Scaling) at the OS layer [14]. Network traffic shaping and/or trans-coding at the middleware layer can be also utilized. Each policy has parameters that can be set to fine-tune the behavior. The policy itself can be regarded as a discrete parameter. In addition, there are hardware parameters that can be set.

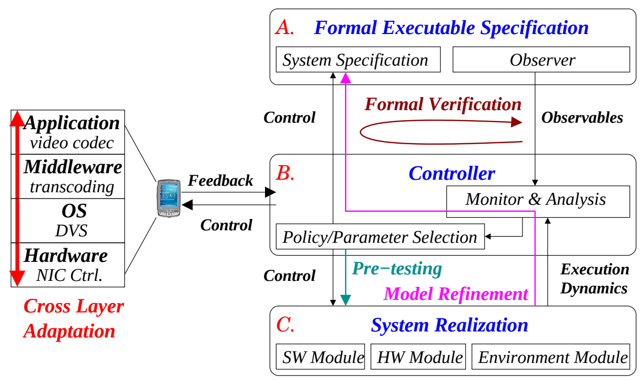

Figure 1: xTune framework for Online Cross-Layer Adaptation by Combining Formal Verification with Observed System Execution Behavior

Clearly, in such a scenario, policies made at one layer can affect behavior at other layers. Thus a *holistic* cross-layer optimization is needed [12]. Therefore, this thesis proposes a unified framework that enables system designers to analyze designs in order to study design tradeoffs across multiple layers and tune the system parameters while predicting the possible property violations as the system evolves dynamically over time.

2 xTune Framework

Figure 1 presents the **xTune** framework [1] that employs iterative tuning using light-weight, on-the-fly formal verification with feedback for dynamic adaptation. We take three major steps:

1. **Modeling, specification and reasoning about cross-layer timing properties:** We propose a novel approach based on concurrent rewriting logic [3] to formally specify and reason about timing issues at all levels of system granularity and study their interrelationships.
2. **Design of policies for addressing QoS/performance based on the cross-layer tradeoffs analysis:** Our work examines the impact of various resource man-

agement techniques on end-to-end timing properties and enables informed selection of resource management policies along with rules for instantiation of parameters that drive the policies.

3. **Reinforcement and proactive control:** We enhance our light-weight formal modeling and analysis by integrating it with system realization to achieve adaptive reasoning and proactive control by providing more precise information on current execution and future state.

3 Research Contributions

Comprehensive analysis of cross-layer QoS-energy tradeoffs and coordinated interaction enable us to tune policy parameters of highly resource limited devices. Specifically, our preliminary study [10] demonstrated the need for integration of formal methods with experimentally based cross-layer optimization methods [2, 12]. Our recent study in [5] proposes an iterative tuning approach for DRE (Distributed Real-time Embedded) systems that couples two important facets: i) a light-weight, on-the-fly formal verification, and ii) a system realization that enables feedback of additional information on dynamic system execution behaviors. In particular, our approach is based on developing an executable formal model specifying a space of possible behaviors and the analysis of these possible behaviors using probabilistic/statistical techniques as presented in [6]. These analysis results enable policy-based operation and adaptation as well as parameter setting of selected policies with quantifiable confidence. The integration of formal analysis with observed system execution behavior permits better analysis of both cross-layer and end-to-end timing/QoS properties for highly distributed systems that employ resource constrained devices.

Continuing this line of research, we propose a compositional cross-layer optimization by coordinated interaction among local (sub-layer) optimizers through constraint refinement [4]. The key idea underlying the compositional optimization is that each local optimizer uses refinement results of other optimizers as its constraints. The resulting constraint refinement can be used as the generic interface among different local optimizers, leading to substantial improvement of solution quality at low complexity.

This thesis work is validated and tested in the context of distributed mobile multimedia applications that present interesting opportunities for tradeoff analysis and enforcement. Many aspects of the application driver are extensively investigated from co-design perspective [13] to experimental study on cross-layer adaptation [12], which includes sublayer optimizations such as video encoding technique with energy/compression/error-resiliency tradeoff [9, 11] (Application layer), energy-aware scheduling policy selection [7, 8] (OS/HW layer), and hybrid dynamic power management with dynamic voltage scaling [14] (OS/HW layer).

4 Concluding Remarks

This thesis presents a unified framework, **xTune**, to develop formal analytical methods for understanding cross-layer and end-to-end timing issues in highly distributed systems that incorporate resource limited devices, and to integrate these methods into the design and adaptation processes for such systems. On top of our framework, we propose a compositional cross-layer optimization by coordinated interaction among local optimizers through constraint refinement. The experiments on a fairly complex case study demonstrate the applicability of our framework — holistic cross-layer optimization by formal verification combining with observation from system realization — to model-based cross-layer adaptation of DRE systems.

References

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Thesis-related Publications

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