

Chapter I

Formal Methods in Cross Layer Modeling and Optimization of Wireless Networks: State of the Art and Future Directions

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ABSTRACT

The layering principle has been long identified as a way to increase the interoperability and to improve the design of telecommunication protocols, where each layer offers services to adjacent upper layers and requires functionalities from adjacent lower ones. In the past, layering has enabled fast development of interoperable systems, but at the same time limited the performance of the overall architecture, due to the lack of coordination among layers. This issue is particularly relevant for wireless networks, where the very physical nature of the transmission medium introduces several performance limitations for protocols designed for wired networks. To overcome these limitations, a modification of the layering paradigm has been proposed, namely, cross-layer design, or “cross-layering.” Several cross-layering approaches have been proposed in the literature so far. Nevertheless, little formal characterization of the cross-layer interaction among different levels of the protocol stack is available yet. A clear need exists for identifying approaches able to analyze and provide quantitative guidelines for the design of cross-layer solutions, and, more importantly, to decide, in each case, whether cross-layering represents an effective solution or not. This chapter provides a detailed survey of the state-of-the-art and future directions in the usage of formal methods for cross-layer modeling and optimization of wireless networks. The text starts by detailing the principles of layered (ISO/OSI and TCP/IP) protocol stacks as well as the cross-layer paradigm. An overview of the architectures of existing and perspective wireless networks is presented along with an analysis of the potential limitations deriving from the layering approach and detailed description of possible optimization solutions enabled by cross-layer design. Subsequent sections are devoted to the issues of modeling and optimization of wireless networks. The remaining

sections cover performance optimization as well as architecture optimization (specifically in terms of signaling). The chapter ends with a summary and outlines about future directions of research on the topic.

INTRODUCTION

ISO/OSI and TCP/IP Protocol Stacks Principles

Currently, design of network architectures is based on the layering principle, which provides an attractive tool for designing interoperable systems for fast deployment and efficient implementation.

ISO/OSI model (Jain, 1993) was developed to support standardization of network architectures using the layered model. The main concepts motivating layering are the following:

- Each layer performs a subset of the required communication functions
- Each layer relies on the next lower layer to perform more primitive functions
- Each layer provides services to the next higher layer
- Changes in one layer should not require changes in other layers

Such concepts were used to define a reference protocol stack of seven layers, going from the physical layer (concerned with transmission of an unstructured stream of bits over a communication channel) up to the application layer (providing access to the OSI environment).

Services between adjacent layers expressed in terms of primitives and parameters:

- Primitives, which specify function to be performed (4 primitives are defined: REQUEST, INDICATION, RESPONSE, CONFIRMATION)
- Parameters, to pass data and control information

A protocol at a given layer is implemented by a (software, firmware, or hardware) entity, which communicates with other entities (on other networked systems) implementing the same protocol by Protocol Data Units (PDUs). A PDU is built by payload (data addressed or generated by an entity at a higher adjacent layer) and header (which contains protocol information). PDU format as well as service definition is specified by the protocol at a given level of the stack.

The same concepts are at the basis of the de-facto standard protocol stack on the Internet, namely the TCP/IP protocol stack (Murhammer & Murphy, 1998).

The main advantage deriving from the layering paradigm is the modularity in protocol design, which enables interoperability and improved design of communication protocols. Moreover, a protocol within a given layer is described in terms of functionalities it offers, while implementation details and internal parameters are hidden to the remainder layers (the so-called “information-hiding” property).

The Cross-Layering Paradigm

Standardization of layered protocol stacks has enabled fast development of interoperable systems, but at the same time limited the performance of the overall architecture, due to the lack of coordination among layers. This issue is particularly relevant for wireless networks, where the very physical nature of the transmission medium introduces several performance limitations (including time-varying behavior, limited bandwidth, severe interference and propagation environments). As a consequence, the performance of higher layer protocols (e.g., TCP/IP), historically designed for wired networks, is severely limited.

To overcome such limitations, a modification of the layering paradigm has been proposed, namely, *cross-layer design*, or “cross-layering.” The core idea is to maintain the functionalities associated to the original layers but to allow coordination, interaction and joint optimization of protocols crossing different layers.

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