Cross-Layer RRM in Wireless Data Networks

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INTRODUCTION

A wireless data network is the infrastructure for mobile computing, which is the act of communicating while on-the-move via portable computers. Hence, wireless data networks (WDNs) and associated issues are enabling technologies for mobile computing. Usually, a WDN does not stand alone; it is connected to the fixed Internet. Hence, it is also referred to as *wireless Internet.* The unit of information transfer and processing in a packet-switched WDN is packet, which is a bunch of bits with the identifying fields needed for efficient forwarding. Advances in digitization enable a packet's content to be of varying nature, such as conversational voice samples, streaming video scenes, or non-real-time data.

Every WDN allowing multiple users to share its services requires a radio resource management (RRM) to coordinate the efficient use of the wireless transmission medium or channel. The wireless channel used by WDNs has time-, frequency-, and environment-dependent quality due to multi-path signal propagation, shadowing, path loss, and user mobility. There are two main RRM philosophies: link/rate adaptation, and opportunistic communications or opportunistic RRM. The link adaptation philosophy views the inherent channel variability as bad and hence mitigates it via complex mechanisms such as interleaving, power control, equalization, and spatial diversity (Gyasi-Agyei, 2005).

Opportunistic communications is the recent RRM philosophy, which exploits the dynamics in wireless channel quality to improve system throughput. In fact, measures have been proposed to enhance or even induce channel variability if necessary to further improve throughput (Viswanath, Tse, & Laroia, 2002). RRM has several functionalities, such as traffic admission control, power control, and scheduling. This chapter focuses on opportunistic communications or scheduling (OS). In fact, link/rate adaptation-based RRM is also somewhat cross-layer protocol engineering, as its uses physical layer information, but for a different purpose than OS. In principle, OS can be designed for single-carrier or multi-carrier, single-antenna or multi-antenna, single-hop or multi-hop, centralized or distributed wireless networks. It can also serve both real-time and non-real-time network traffic. However, it is much easier to design an OS scheme for single-hop, centralized wireless networks serving non-real-time data traffic. The achievable throughput gains are also maximized when no traffic timing constraints are embedded in the OS policy.

Scheduling is the dynamic process of allocating a shared resource to multiple parallel users in order to optimize some desirable performance metrics. Metrics of interest include: maximization of system throughput, minimization of packet delay and jitter, and the provision of fairness. Scheduling is a key mechanism in RRM and operates in the medium access control (MAC) layer. Only three things can happen to the transmission medium of a multiuser network: resource hogging, resource clogging, or equitable resource sharing. Without a MAC protocol, the desirable third option can hardly occur. In the following we discuss some general aspects of OS, propose a generalized OS design framework, discuss future trends of OS, and list some open issues in OS design.

BACKGROUND

This section reviews some background material on OS.

Why Cross-Layer Protocol Engineering?

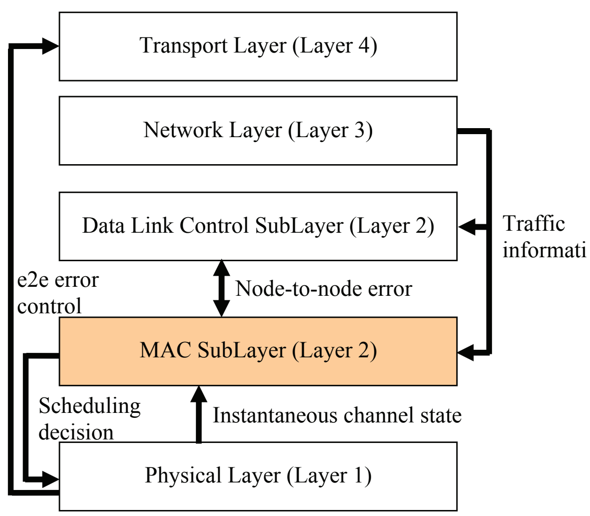
A protocol is a set of agreed-upon rules by which two entities communicate efficiently. This includes both semantics and syntax. The telecommunications industry has been sustained so far by the open systems interconnect (OSI) reference architecture designed by the International Standards Organization (ISO). Hence this architecture is referred to as the ISO/OSI model. The ISO/OSI model is a brick-wall protocol architecture whereby the functions of a complete workable communications system is broken into a set of functionalities (not without duplications) and each set is called a layer. Each layer provides a service to the overlying layer. However, the service user is not privy to how the service is provided, and neither does it know the features of its service provider. Non-adjacent layers on the same machine have no interaction, but layers at the same level on two machines communicating interact logically to exchange data and signaling. This horizontal interaction is referred to as *peer-to-peer communication.* Indeed, no practical system is strictly designed according to the ISO/OSI model. However, the popular protocol used on the Internet, TCP/IP model, is designed based on the ISO/OSI philosophy.

The ISO/OSI philosophy has been embraced so far as great, as its modularity enables upgrading of one layer with minimal impact on other layers, until the recent drive towards system performance optimization via cross-layer engineering.

Table 1. Protocol layering and modularity vs. protocol efficiency

Layering Protocol Engineering	Cross-Layer Protocol Engineering
Traditional protocol design approach	Modern protocol design approach
Modularity oriented	Efficiency oriented
Strict layering abstraction, no interactions between non-adjacent protocol layers on the same machine	Exploits inter-layer interactions to optimize overall system performance
Partitioning of protocol functionalities reduces protocol complexity	High computational complexity
Allows protocol specialization	Requires interdisciplinary knowledge
	Incompatible with existing protocols
Easy to manage and maintain	Complicated system management and maintenance
	Revolutionary approach to system design
Only lower protocol layers are network specific	Entire protocol may be network specific
	Can reduce device energy consumption

Figure 1. An OS algorithm showing cross-layer signaling exchanges



This new era of *cross-layer protocol engineering* has opened both opportunities and challenges for protocol designers. Fourth-generation networks and beyond are expected to exploit the benefits in cross-layer protocol engineering (Shakkottai, Rappaport, & Karlsson, 2003). *Cross-layer protocol design leverages runtime information across different layers to enhance the performance of the entire wireless system.* It can also be used to reduce functionality duplications during protocol design. The idea originates from the notion that layers can adapt to the instantaneous condition of other layers to improve the overall service provided to network applications. Table 1 summarizes the basic features of both protocol design philosophies.

Figure 1 illustrates the design of a cross-layer wireless scheduler. We can observe interactions in several directions between layers 1-4. These inter-layer interactions can allow higher layers to adapt to the random variability in physical layer properties to optimize system performance. Specifically, Figure 1 shows channel state information (CSI) from Layer 1 and traffic information from Layer 3 communicated to Layer 2, where the scheduler operates. These parameters enable the MAC layer to make informative decisions. For example, the

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