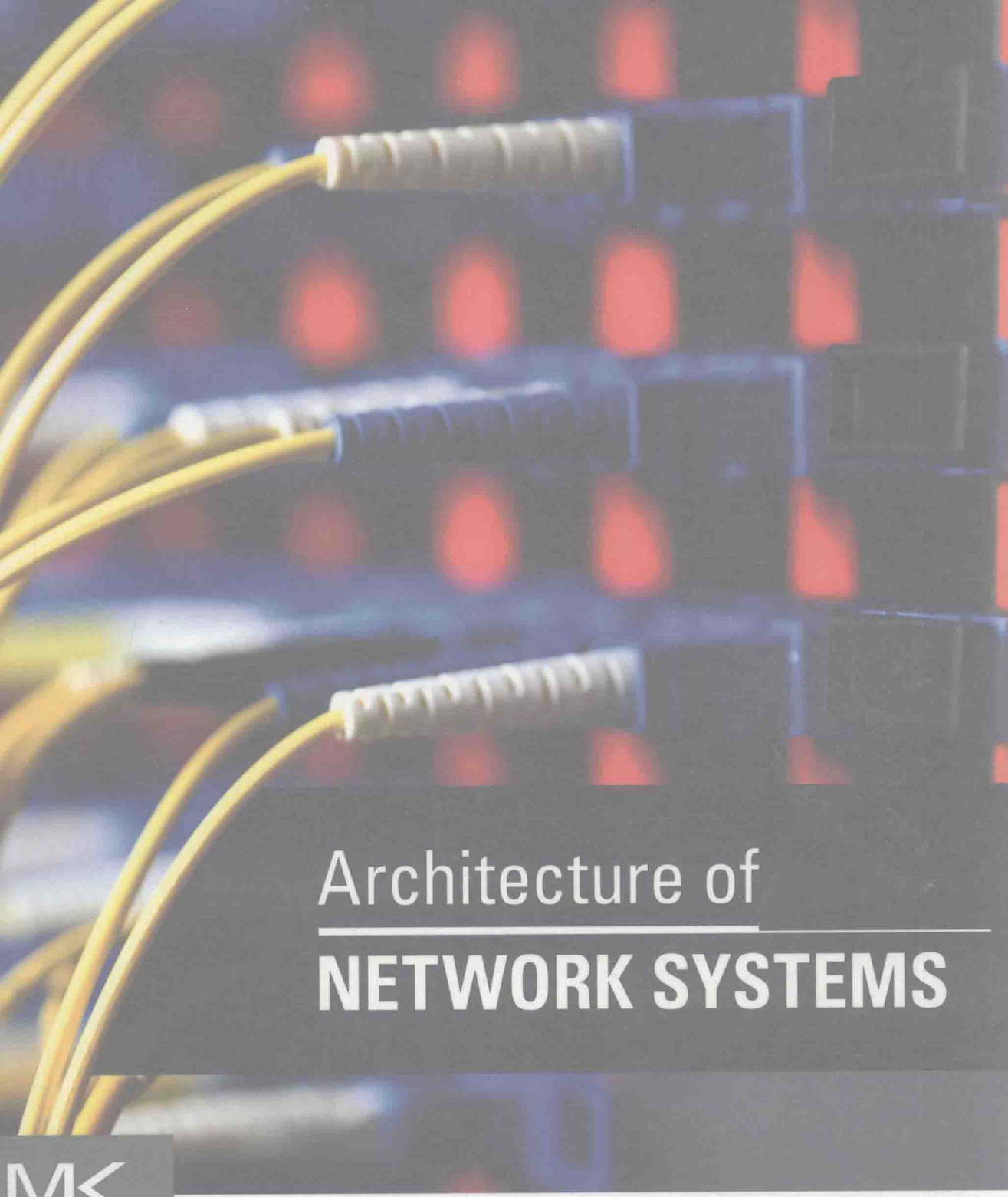

Architecture of NETWORK SYSTEMS

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Architecture of Network Systems

To the memory of my father Nikolaos. -DS
To Ana and our daughter Susana. -TW

Preface

WHY WRITE THIS BOOK?

Data communication networks are widely used today and are an integral part of our daily life. The Internet is a medium for business, personal, and government communication, and it is difficult to envision today's society without this essential infrastructure. The continued success of the Internet is dependent on our ability to maintain and improve the functionality, performance, and scalability of these networks. As a basis for obtaining the necessary knowledge about networks, there is a clear need for textbooks that provide an introduction to the foundations of this topic as well as a detailed understanding of more advanced issues.

While many available books cover the design of network protocols and their operation, there has been preciously little focus on the systems that implement networks. Early data communication networks struggled with the scarcity of transmission bandwidth, which led to significant efforts to improve management and efficient use of this resource. Over the last three decades, advances in transmission technology have led to the availability of vast amounts of bandwidth, thus shifting the main bottleneck of networks from the transmission medium to the switching and processing of transmitted data. As a result, modern networks and the Internet are not only in need of appropriate protocols for the wide deployment of applications and services, but also in need of efficient systems that enable the timely processing and forwarding of network traffic.

TARGET AUDIENCE

This book aims to serve as a textbook and reference for designers and implementers of networking technology, networking students, and networking researchers. The goal of the book is to present the systems issues of network systems, approaching them from the architecture, design, and implementation point of view. Considering that network systems are embedded systems that implement network protocols, readers of the book would benefit from being familiar with the basic concepts of networking, embedded systems, and computer systems organization and architecture.

APPROACH

This book is about computing systems or, more specifically, about a class of special-purpose embedded systems used in networking devices. As such, the main thrust of the book is the promotion of systems architectures and designs. Therefore, this book can be classified as a computing systems book.

In contrast to typical architecture and computing systems books, this book follows a structure analogous to those of typical networking books. Following the OSI reference model for network protocols, a model that has been proven highly valuable from an education point of view, we classify and present network systems and their designs. Later in the book, we also discuss specific components of network systems, similarly to books on system architecture.

Since this book is the first systematic effort to present the architecture of the complete range of network systems as a whole, we focus on promoting key concepts for all types of network systems. We attempt to present the main architectures and designs of systems and components that cover this area. Clearly, the book does not and cannot cover all existing material in this area, which has experienced fast growth in recent years. Instead, the book focuses on major concepts. In addition to presenting state of the art, we have tried to demonstrate the progress in the field during the last couple of decades through specific examples that illustrate the improvements of technology and indicate the path of evolution for network systems in the future.

COURSE USE

This book has been specifically developed for use in college courses at the upper undergraduate level and graduate level. Much of the material presented in this book has been used previously by the authors in a graduate and advanced undergraduate course on network systems architecture of the Department of Electrical and Computer Engineering at the University of Patras and in a graduate level networking course of the Department of Electrical and Computer Engineering at the University of Massachusetts Amherst. It is expected that students taking a course based on this book have some prior exposure to computer networks and computer system organization. While the Appendix of the book provides a brief overview on the network protocols used in the Internet, a more detailed course on this topic may be of value.

It is not necessary to cover the entire book in a course. While there are some dependencies between chapters, different courses can emphasize different characteristics of network systems. For courses that address the networking aspects of network systems, we suggest a focus on Chapters 4 through 10, while for courses that address the embedded system aspects of network systems, we suggest a focus on Chapters 11 through 14.

WE WANT TO HEAR FROM YOU

We would appreciate receiving any feedback you may have about the book. Tell us if you find mistakes, if you have suggestions for improvements, what you like about the book, how you have used it in a course, etc. You can contact the authors via email at serpanos@upatras.gr (Dimitrios Serpanos) and wolf@ecs.umass.edu (Tilman Wolf).

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About the Authors

Dimitrios Serpanos is a Professor of Electrical and Computer Engineering at the University of Patras, Greece, and the Director of the Industrial Systems Institute (ISI/RC Athena). Currently, he is also the chairman of the governing board of the newly founded University of Western Greece. His research interests include embedded systems, with focus on network systems, security systems and multimedia systems, computer architecture, and parallel and distributed systems.

Serpanos holds Ph.D. and M.A. degrees in Computer Science from Princeton University, Princeton, since 1988 and 1990, respectively. He received his diploma in Computer Engineering and Informatics from the University of Patras in 1985.

Between 1990 and 1996 he was a research staff member at IBM Research, T.J. Watson Research Center, New York. Since November 1996 he has been a faculty member in Greece. Between 1996 and 2000 he was with the Department of Computer Science, University of Crete. Currently, he is with the Department of Electrical and Computer Engineering, University of Patras, where he is a professor. During his term in Crete he conducted research at ICS-FORTH; while in Patras he has been conducting research at ISI. Professor Serpanos' research has received funding from the EU, the Greek government, and the private sector in Europe and the United States.

Serpanos is a senior member of the IEEE, a member of the ACM, a member of the New York Academy of Sciences, and an educational member of USENIX. He is serving or has served as associate editor for technical journals, including *ACM Transactions on Embedded Computing Systems*, *IEEE Transactions on Industrial Informatics*, the *Journal of Internet Engineering*, and *International Journal on Computers and Their Applications*. He has served as general chair and TPC chair of several conferences and workshops, as well as a TPC member of more than 120 conferences and workshops. In addition, he has served as guest editor to special issues of *IBM Journal of Research and Development*, *IEEE Network*, *ACM Transactions on Embedded Computing Systems*, IEICE/IEEE joint issues, and *Telecommunication Systems*.

Tilman Wolf is an Associate Professor in the Department of Electrical and Computer Engineering at the University of Massachusetts Amherst. He is engaged in research and teaching in the areas of computer networks, router design, embedded systems, and network and system security. Wolf received a diploma in Informatics from the University of Stuttgart, Germany, and holds a D.Sc. in Computer Science and two M.S. degrees from Washington University in St. Louis.

Wolf started working in the area of router design and network processor design in the late 1990s when commercial interest in routers with programmable data paths started taking off. His worked focused on the design of high-performance routers that use programmable port processors to provide dynamically changing functionality, with an emphasis on performance modeling and benchmarking.

Since joining the University of Massachusetts in 2002, Wolf and his students in the Network Systems Laboratory have designed and prototyped run-time systems for workload management across multiple embedded processor cores in packet processors. Their work also addresses the question of how to redesign Internet architecture to balance the need for custom networking functions with the need for simplicity and manageability. More recently, he and his students have explored security vulnerabilities in processing components of network systems that require embedded protection mechanisms.

Wolf is a senior member of the IEEE and the ACM. He has served as associate editor for the *ACM/IEEE Transactions on Networking*, as program committee member and organizing committee member of numerous professional conferences, including IEEE INFOCOM and ACM SIGCOMM, and as TPC chair and general chair for ICCCN. He has served as treasurer for the ACM SIGCOMM society for several years. He has received several recognitions for his educational activities, including a college outstanding teacher award.

Contents

CHAPTER

Architecture of network systems overview

1

Computer networks have become critical infrastructure on which we rely for personal, business, and government use. Network systems are the hardware and software components from which these networks are built. Network systems determine what functionality a computer network can provide and what performance it can achieve. Due to this critical role, we believe it is important to study the architecture and operation of these network systems.

Network systems draw from concepts and technologies in computer networks, embedded systems, computer organization, and distributed computing. The convergence of these very diverse technical areas makes the study of network systems particularly exciting. This diversity also requires a thorough understanding of the relationship between these areas and how they influence network system design. We hope to provide these insights in this book.

COMPUTER NETWORKS

The advances of transmission technology for more than two decades have brought significant changes in networking as well as computing. In the 1970s and 1980s, standard networks provided limited connectivity, achieving bandwidth in the order of kilobits per second (kbps) up to a few megabits per second (Mbps) for local area networks, where the maximum speed reached 10 to 16 Mbps. From the middle of the 1980s, the development and commercialization of high-speed links that provided bandwidth of several Mbps for point-to-point connectivity enabled development of a new generation of networks and protocols that enable communication at very high speeds, reaching today hundreds of gigabits per second (Gbps).

In parallel with the dramatic progress in transmission technology, in the last decade of the 20th century the Internet was commercialized, moving it from research use to commercial use. The need to provide Internet connectivity to end users at home and at work not only exploited the high-speed transmission technology that had been developed, but also led to significant progress in access technologies. This trend led to development of a wide range of access protocols to connect end users to the Internet through telephone lines, cable TV infrastructure, satellites, and so forth.

The deployment of high-speed links and networks, as well as the Internet, provided the infrastructure for the development of new computing paradigms, mainly network-centric computing. In this paradigm, newly developed system infrastructures are used to support computing and storage-intensive applications and services. An early characteristic example is the development of networks of workstations, a multiprocessor architecture that relies on high-speed connectivity among workstations. This multiprocessor model is a natural advance of traditional distributed systems, which connected autonomous computing systems; the single view of the network of workstations as one system, necessary for a multiprocessor, was enabled by the high-speed networks that had become available. This abstraction enabled the efficient management of distributed resources through appropriate computing models and enabled a unified view of the networked workstations to the users. In a different direction, the ability to provide access to data and computational resources over the Internet enabled a vast number of new services for users and customers of commercial enterprises. These services are based on the well-known client/server distributed computing model and include examples ranging from banking to news feeds and from video conferencing to digital libraries.

The provision of all these services and applications over networks, including the Internet, requires technological advances at two fronts: protocols and network systems. Network protocols define the methods and mechanisms necessary to achieve reliable communication between two parties (or more than two in the case of multicasting or broadcasting). For example, network protocols define methods with which data units are encoded for transmission, mechanisms to detect transmission errors, methods for retransmission of data in case they are lost or transmitted with errors, and methods for regulating the flow of information between communicating peers to ensure that the receiver is not flooded with incoming data. Importantly, network protocols do not define any aspect of the systems that execute these protocols in order to implement data communication. For example, protocols do not define the type of processors, their speed, the size of memory, or any other systemic characteristic of the devices that implement these protocols.

Network systems are the systems and subsystems that realize the implementation of network protocols. Network systems need to be designed to meet the functional requirements specified by protocols. They also need to meet the performance requirements determined by the ever-increasing speed of transmission links. This relationship between network systems and related areas is illustrated in Figure 1-1. The demands for executing protocols at high speed led to the need for advanced, sophisticated system architectures, component designs, and implementations. These network systems constitute the focus of this book.

Network systems represent a distinct area of embedded systems architecture. Network systems are embedded systems because they are embedded in autonomous systems and devices that have specific purposes. For example, network systems are present in the infrastructure of networks, such as in switches, bridges, routers, and modems. Importantly, network systems also include network adapters,