MODELS AND LAYERED PROTOCOL ORGANIZATION

Joan Garcia-Haro, Josemaría Malgosa-Sanahuja, Pablo Pavón-Mariño, and **Javier Vales-Alonso**
Polytechnic University of Cartagena, Spain

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Contents

Summary

This chapter introduces the basis of communication protocols design. The concept of protocol is intrinsic to any communication process. It can be defined as the set of previous agreements between the sender and receiver about all relevant issues present in the communication, i.e. the messages defined in the protocol, their format, etc…, or the actions taken under any message event. The advances in communication networks have powered a growing complexity in communication protocols. Protocol Engineering is devoted to cope with this complexity, finding the ways to make sure that the set of rules forming a protocol guarantee a satisfactory operation under any event. This requires formalizing and structuring the descriptions, making all the assumptions explicit. The main ideas behind Protocol Engineering are presented in this chapter. Nowadays, communication protocols employed in modern networks are structured in layers, so that protocols at different layers collaborate to address the possible difficulties that may arise in the communication between two users. The most common layering approaches are also presented in this chapter. Afterwards, a set of relevant existing communication protocols are exposed to exemplify the issues present in protocol design.

1. Introduction

Communication is one of the most important abilities of human beings. It is intrinsically embedded into the human behavior and needed to perform almost all human activities. By nature the human body structure allows us to communicate each other by using some of its organs like the mouth, the vocal chords, the ears, the eyes and the hands. However, all these facilities cannot be directly used when the distance between the speaker (sender) and the listener (receiver) is long enough. In this scenario, we have to incorporate an additional element –called technology- that has the responsibility to efficiently transmit our sounds (or signs or images) throughout the environment (the communication channel), i.e. the air.

A communication protocol can be defined as a kind of agreement about the exchange of information between the sender and receiver. A full protocol description looks much like a language definition:

- It defines a specific format for valid messages (like dots and dashes in the Morse code).
- It defines a grammar, that is, a set of procedure rules.
- And finally, it defines a vocabulary of available messages with their meaning.

A communication protocol uses some type of technology to transmit the information from the sender to the receiver(s). That is, we have to differentiate between the protocol and the technology employed to exchange messages using this protocol. The first communication mechanisms were too elemental and as a consequence, the protocol and the associated technology were not easily distinguished. Indeed, this situation may occur in today telecommunication facilities and sometimes the terms “network” and “communication protocol” are used with the same meaning.

1.1. Brief History Overview

Communication protocols have been defined and used along the history by several civilizations, although, unfortunately, only few of them were well documented. During the last century -coinciding with the discovery of the electricity- the (tele)communications protocols began to spread around. Mainly, thanks to the fast development and growth of the associated electrical/electronic communications technologies. However, it is interesting to briefly summarize some of the methods and protocols used by the ancient civilizations to communicate.

The first reference, due to the Greek historian Herodotus of Halicarnassus (BC. 484-424), is in the book entitled *The History*. He describes how Phidippides ran nearly 250 Km from Athens to Sparta to obtain the support of the Spartans in a battle with the Persians. In fact, the references of runner messengers are common throughout the history, and they were also used by Egypt, China and Babylon civilizations. Often, the runner messengers suffered attacks from enemies and, to solve this problem, the early Babylonian kings decided to place royal soldiers at regular distances along the roads. Although initially they were intended for protection, their presence improved the performance of the messenger system. They were used as a relay system, where a message was passed from one guard station to the next, each time moved by a new runner (this feature is called *hop by hop* communication and is still widely used in nowadays data communication networks). Besides, each guard post was equipped with a fire beacon to quickly transmit alarm signs without the need of a human runner. Herodotus also described a new improvement, this time initiated by the Persians: the use of horses instead of humans. Therefore, the time spent to transmit a message was reduced and the guard stations could be more separated (reducing costs). As described by Suetonius, the Roman Empire also used this method and Marco Polo wrote about a similar relay system used by the Mongols. Sometimes, pigeons replaced horses. In fact, pigeons were even used during the First World War by the British Air Force.

Another ancient communication mechanism, first time mentioned by the historian Plutarch, was the use of flags. Their use was elemental until 1738, when the Frenchman Bourdonnais introduced a numerical code for flags. Some time later, in 1763, another Frenchman called Bigot published a new code book which specified a true protocol for the use of coded flags. He established some fundamental concepts in communication protocols design, still used in current data networks, like synchronization, acknowledgement of received signals and broadcasting a signal throughout the entire set of participants. The British Navy first adopted the same methodology in 1790 that was further extended to all Europeans Navies.

Not surprisingly, the telegraph appeared just before the electric age arrived. The first optical-mechanical telegraph was developed by the French Claude Chapper in 1793, but followed by the British Lord George Murray and the Swedish Abraham N. Edelcrantz. All of them built a useful telegraph network in their own countries. Mechanical devices like beacons, shutters, gears, pulleys, etc., composed the system. They also used a telescope to enlarge the distance between post offices, always situated at the top of hills or church towers.

The advances in electronics changed drastically the communication systems and protocols, also called telecommunication systems. The first electric telegraph was patented in 1837 by William Cooke and the first telephone in 1876 by Alexander Graham Bell (Elisha Gray lost her rights to a similar invention by only three hours). In 1897 Guiglielmo Marconi built and used the first radio telegraph. All these telecommunication systems and their associated networks grew quickly, reaching each distant corner.

The next communication network and protocol revolution roughly happened in 1956, when a protocol based on the Master-Slave paradigm was used to communicate two long distance computers across telephone wires. This event could be observed as the beginning of the Internet, which became a reality in 1969 with the foundation of the Advanced Research Projects Agency Network (ARPANET). However, some authors consider that January 1st 1983 was when the Internet started, since, at that date, all the hosts and routers connected to ARPANET simultaneously were set up to understand the famous TCP/IP (*Transport Control Protocol/Internet Protocol*) protocol stack. After this, the amount of communication protocols has grown exponentially since each electronic device (consumer electronics, sensors …) uses some kind of communication facility.

Finally, it should be noticed that one of the first explicit descriptions of a data transmission method was written by the Greek historian Polybius (BC. 203-120). He said "(…) things that can happen, but cannot all be foreseen *–and it is chiefly unexpected occurrences which require instant consideration and help*- all such matters defied communications by fire signal". The crucial observation -shown in cursive- is still a real problem. The unexpected sequences of events that lead to protocol failures are the most troublesome issue in protocol design since we must try to expect the unexpected. In August of 1861, 21 people died and 176 were injured because the protocol used to control a train tunnel (by means of a telegraph system) had inconsistencies under unexpected events.

1.2. Protocol Standardization

The use of standard protocols has some important benefits like worldwide compatibility, technical business community support, high development degree and high quality and reliability. If communication devices agree with standard communication protocols, the manufacturers can take advantage of economies of scale. Thereby, the standards contribute to a more efficient development, manufacturing and supply of communication products and services.

There are many organizations in charge of communication protocol standardization. Almost all of them are mainly composed of private companies (except two Internet related standardization bodies, which are not sponsored by private manufacturers). Although they agree about what the protocol must do, they obviously compete in the way the protocol is implemented.

Some of the most relevant communication standardization organizations are:

- The International Organization for Standardization (ISO) is a network composed of the National standard institutes from more than 150 countries, with a Central Secretariat in Geneva that coordinates the entire system. Although some of their members are part of the governmental structure of their countries, other members have their roots only in the private sector. ISO has published a lot of international standards ranging from traditional activities, such as agriculture or construction, through mechanical engineering, to the newest information technology developments. Some of the most well-known OSI communication protocol standards are the ASCII character code, the RS-232 serial interface definition and the Open System Interconnection (OSI) framework. The most well-known ISO standards (not related to communication protocols) are the 9000 and 14000 families, concerned with business quality and environmental management respectively.
- The International Telecommunication Union (ITU) consists of three sectors: the Telecommunication (ITU-T), the Radiocommunication (ITU-R) and the Telecom Development (ITU-D). The first one is concerned with communication protocols. It was created in 1993, replacing the former International Telegraph and Telephone Consultative Committee (CCITT). ITU-T contributes to produce an efficient set of recommendations covering all fields of telecommunications, like network access technologies, electrical, optical and mobile networking, network operation and management, signaling protocols, tariff and accounting issues, etc. ITU-T is formed mainly by public and private telecommunication companies and by scientific, industrial and financial institutions. To become a member, the approval of the Administration of the Member State is needed, except for a Regional or other international telecommunication, standardization, financial or development organization.
- The Internet Engineering Task Force (IETF) is a large open international community of network designers, operators, vendors and researches concerned with the evolution of the Internet architecture and its operation. It is open to any interested individual. There are eight operating areas managed by one (or more) Area Director: applications, general, Internet, operation and management, real-time applications, routing, security and transport. In addition, each area consists of a variable number of working groups. Each working group produces Internet-drafts and RFC (Request for Comments) documents, although the first ones are not archival document series since in six months, they may turn into RFC or die. A RFC is the official IETF document describing the standard and has different status: standard, proposed standard, draft, experimental, and informational.
- The Internet Research Task Force (IRTF) is similar to the IETF but focusing on research topics related to Internet protocols, applications, architecture and technology. Often, the standards approved by the IETF were before a research topic in the IRTF.
- The Institute of Electrical and Electronics Engineers (IEEE) is a non-profit professional association for the advancement of technology. The areas of interest cover from aerospace, computer and telecommunications systems to biomedical,

electric power and consumer electronics among others. The IEEE 802 series are the most popular standards of this organization, all of them related with the Local Area Network (LAN) technology. For example, the 802.3 standardize the CSMA/CD multiple access method used in Ethernet networks and the 802.5 do the same but with Token Ring networks. The IEEE also standardizes wireless networks in the 802.11, 802.15 and 802.16 series. All the 802 standard documentation can be downloaded in electronic format free of charge from the IEEE web page.

2. Protocol Structure

2.1. Introduction

In the previous section, communication protocol is defined as an agreement among two or more communicating points reached to control the exchange of information. Once the transmission media has been chosen, a set of rules are required for its proper use. This implies determining the actions taken for every possible event, for instance, how a transmission is initiated or terminated, how message delivery faults are handled and so on. The first main concern in protocol design lies in the difficulty to plan a complete set of rules with no contradictory procedures, which guarantee a satisfactory operation under any event. In fact, Protocol Engineering is dedicated to find the ways to make sure that the set of rules forming a protocol is both complete and consistent. This requires us to formalize and structure the descriptions, making all the assumptions explicit.

In this way, a protocol specification consists of five distinct parts:

1. The *service* the protocol provides.
2. The *assumptions* about the environment: (i.e. the transmission media).
3. The *vocabulary*. That is, the messages defined in the protocol.
4. The *encoding* of each of the messages specified in the vocabulary.
5. The *procedure rules* to guard the consistency in protocol operation. It includes the actions taken under any message event.

The last element of the protocol is the most difficult objective to accomplish. In fact, given a set of procedure rules, the verification process about its consistency is a major issue in Protocol Engineering. The protocol rules must face a set of subtle problems given by the requirement to react to any sequence of message events, which cannot always be predicted. Abnormal operation of hardware may produce a rare sequence of events, under which the protocol must maintain a consistent operation. In general, the number of possible ordering of events is overwhelming, and avoids any attempt to analyze protocol behavior by means of manual case analysis.

In the next section, further description to the five parts devised in structured protocol design is provided, which can help to a successful protocol specification.

2.2. Service Specification, Environment Assumptions and Protocol Vocabulary

The definition of the service a protocol provides, involves enumerating the input events which can be received from the user and the outputs produced. Next, an example of a protocol responsible for providing a reliable communication between a client database and the database server is introduced. The inputs to the protocol are defined as the set of database queries and the possible success or error events that can be produced from the query. In this way, a protocol service specification defines a protocol as a black box, where the actual actions taken by the protocol to accomplish the defined task are hidden. From the implementation point of view, as reliability is included as a part of the service, error recovery techniques must be implemented guaranteeing a reliable message transmission. Besides, if client and server database applications are assumed to be running on different computers in a network, it is required a mechanism which enables client and server endpoint messages to find their way to the other endpoint. This involves designing an addressing scheme, so that each possible message endpoint is assigned a different identifier. The routing decisions to take in the network should be also defined. Focusing on the physical parameters of the links in the network, a large list of functions arises, which should be specified as well in the protocol: synchronization, detection, etc.

The first part of the structured protocol design list is still dealt and seems an overwhelming task. Common sense suggests what to do with this type of large problems: “divide and conquer”. That is, they are divided into subproblems that are either easier to solve or have been solved before. Protocol service specification has followed this strategy by structuring the protocol designs in *layers*. Basically, each layer is responsible for solving a set of issues involved in the communication between endpoints, so that each layer provides a *service* to its upper layer, using the service provided by its lower layer. The latter are the *assumptions* the protocol makes about the environment.

The benefits of a layered design are similar to those obtained from any modular approach: it helps to provide a logical structure of the protocols, separating higher level from lower level tasks and allowing the replacement of layers, instead of rewriting an entire protocol.

In 1980 the International Standards Organization (ISO) adopted the layered approach and defined a hierarchy of seven layers as a reference model for communications protocol design: the OSI model (Open System Interconnection, figure 1).

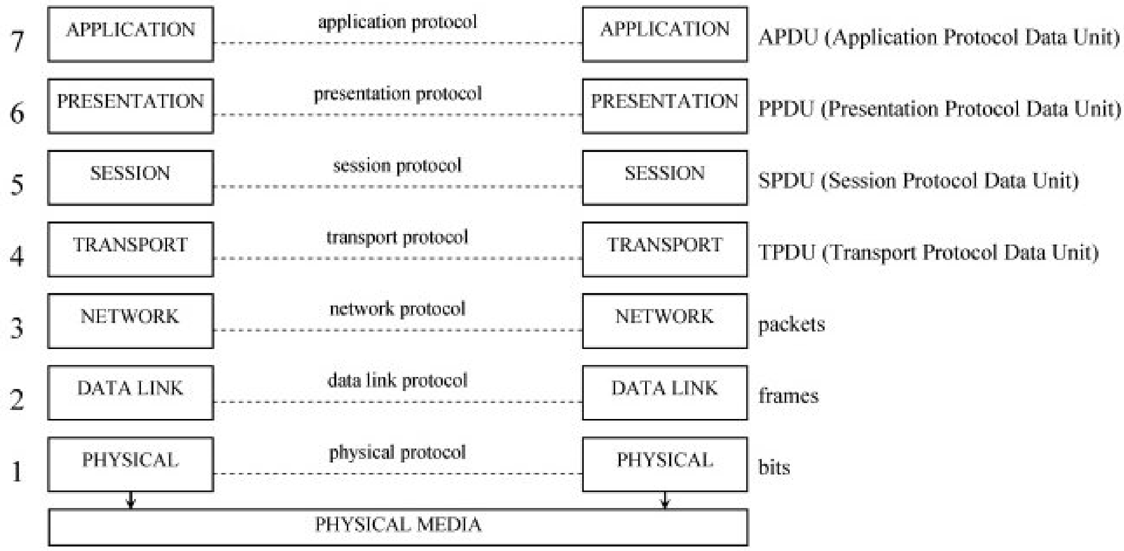

Figure 1: Open System Interconnection Architecture

- Physical layer: This is the only layer which interacts with the physical media. It performs the actual transmission of the information through the media. Both endpoints of the media must agree in issues like voltage, coding, modulation, etc.
- Data link layer: It offers the possibility to transmit series of bits (called frames) through the physical layer. This means that, at least, it implements the required techniques to unambiguously separate consecutive frames. Other functions like error detection and recovery can be included in the data link layer service.
- Network layer: Its main function is the routing of the messages in a network of nodes, from the source endpoint of the message to the destination endpoint. This entails defining an addressing scheme, routing procedures and congestion control techniques.
- Transport layer: This layer and the following ones are designed to run only in the source and target endpoints, where the end user applications are also running. In general, transport layers are responsible for providing a reliable communication and flow control between end applications.
- Session layer: This layer introduces to the upper layer the concept of session between end applications, interacting with the underlying transport protocol.
- Presentation layer: This layer defines a user-level syntax of the messages and provides functionalities about data format like encryption or compression.
- Application layer: This layer interacts with the true communicating application.

Figure 2 illustrates the main concepts of a layering technique. In the communication between two endpoints A and B, the *n*-th layer implemented in each side (A_n and B_n) exchanges protocol messages, which are denoted as PDU_n (Protocol Data Unit, level *n*).

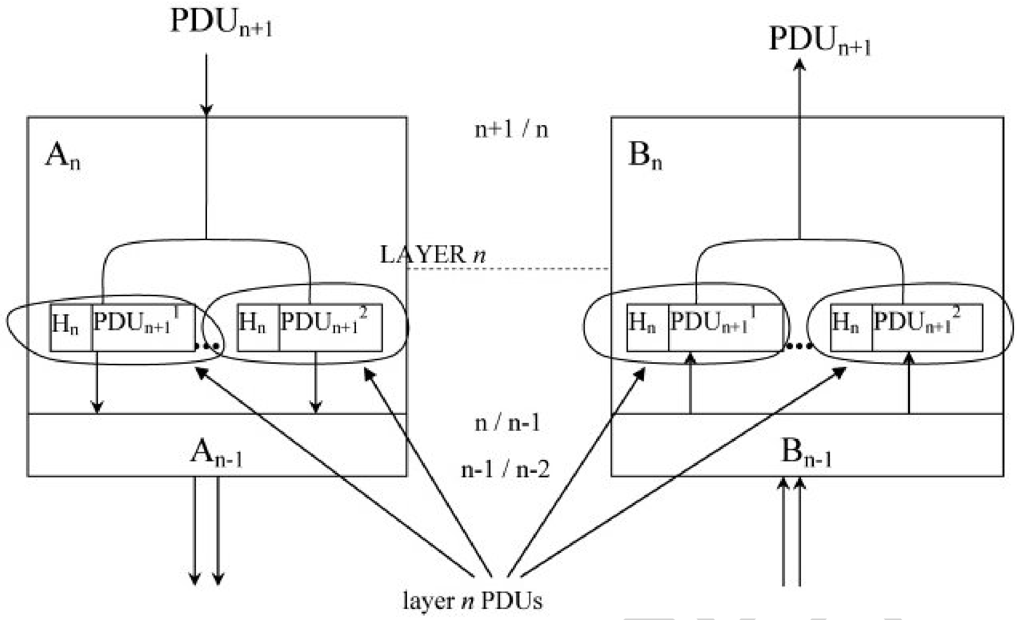

Figure 2: Peer entities

- The service offered by the n-th layer is defined by specifying the *interface* between n layer and $n+1$ layer. This includes the set of available calls –or *primitives*- the implementation in $n+1$ layer can invoke in n layer protocol.
- In order to accomplish the tasks associated to the service the n layer protocol agrees to provide, it invokes the required and available primitives in its lower $n-1$ layer. The $n-1$ layer service defines the n layer assumptions.
- A_n and B_n are denoted as *peer entities*, which exchange and process PDU_n messages to implement the service provided to the $n+1$ layer. The set of PDU_n messages defined in a n layer protocol is the *protocol vocabulary*. It is important to remark that the n layer protocol specifies the set of rules which govern the exchange of PDU_n messages. However, the actual implementation details inside an n layer entity, which are hidden from the other layers, are not standardized.

The exchange of PDU_n messages between peer entities in n layer faces communication issues such as the need of a flow control mechanism, reliability, routing, congestion control, etc. Fortunately, the “divide and conquer” strategy implies that all the required mechanisms do not have to be implemented in every layer but they are distributed among layers. The set of specifications of protocol layers, together with their interfaces, is called a *protocol architecture* or *protocol stack*.

Figure 2 helps to introduce a relevant concept in layered protocol design: the protocol encapsulation.

In normal operation, a layer n protocol receives a layer $n+1$ PDU through its upper interface. In order to accomplish the task of transporting the PDU_{n+1} message to its peer endpoint, the layer *n* protocol requires the transmission of a variable number of PDU_n messages. Each one carries two types of information.

- Control information: To be processed by the layer *n* protocol in the target endpoint.
- Data information, composed of the PDU_{n+1} messages to be transmitted. Each layer n protocol manages upper layer $PDUs$ as opaque data.

In the example, layer *n* control information is included in the PDU_n header and layer $n+1$ PDU is included in an opaque data field: $PDU_n = \{header_n + PDU_{n+1}\}$. This procedure is called protocol encapsulation, as a layer $n+1$ PDU is encapsulated in a PDU_n message, and so on. At the reception side, a layer *n* implementation receives the PDU_n message from its lower layer, processes header$_n$ information and transfers the opaque data to its upper layer. In the figure, layer *n* service includes the segmentation and reassembly functionalities. Then, it may fragment the PDU_{n+1} data in several PDU_n messages. $Header_n$ bytes should include the required control information to allow the receiver to assemble the fragments that compose the original PDU_{n+1} message.

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Bibliography

A. Tanenbaum, “Computer networks”, 4th Edition, Prentice Hall PTR, ISBN 0-13-066102-3. [A comprehensive synopsis of data communication networks.]

Bertsekas, R. Gallager, “Data Networks”, Prentice-Hall International Editions (second edition), ISBN 0-13-201674-5. [A comprehensive and exhaustive description about the most remarkable aspects related to data networks]

Bruce Carlson, “Communication Systems. An Introduction to Signals and Noise in Electrical Communication”, McGraw-Hill International Editions (third edition), ISBN 0-07-009960-X. [A detailed study about the communications systems, considering both analog and digital communications]

G. J. Holzmann, “Design and Validation of Computer Protocols”, Prentice-Hall software series, ISBN 0-13-539925-4. [An excellent survey about the methodologies for efficiently validate communication protocols]

W. Richard Stevens, “TCP/IP Illustrated: the protocols”, Vol.1, Addison-Wesley professional computing series, ISBN 0-20163346-9. [A detailed revision about the most relevant Internet protocols.]

Biographical Sketches

Joan García-Haro received the Telecommunication Engineering degree and the Ph.D. in Telecommunications in 1989 and 1995 respectively, both from the Polytechnic University of Catalonia (UPC), Spain. He has been an Assistant Professor at the Department of Applied Mathematics and Telematics (DMAT-UPC) since 1992, and Associate Professor since 1997. In September, 1999 he joined the Polytechnic University of Cartagena (UPCT), Spain, where he is a Professor of the Department of Information Technologies and Communications. He has been involved in several National and International research projects related to electronic and optical packet switching, B-ISDN design and planning, next generation Internet, wireless and sensor networks, value-added services and performance evaluation issues. He was a visiting research scientific at Queen's University at Kingston, Ontario, Canada. He is author or co-author of more than 50 papers mainly in the fields of switching and performance evaluation. Since 1994 he served as regional correspondent of the Global Communications Newsletter (and Editor in Chief from April 2002 to December 2004) included in the IEEE Communications Magazine, Associate Technical Editor from January, 2000, and Technical Editor of the same magazine from March 2001. He also holds an Honorable Mention for the IEEE Communications Society Best Tutorial paper Award (1995).

Josemaría Malgosa-Sanahuja received the Telecommunication Engineering degree in Telecommunications in 1994 from the Polytechnic University of Catalonia (UPC), Spain. In November 2000, he received the Ph.D. degree in Telecommunication from the University of Zaragoza (UZ), Spain. He has been an Assistant Professor at the Department of Electronic and Communications Engineering (University of Zaragoza) since 1995. In September 1999, he joined the Polytechnic University of Cartagena (UPCT), Spain, as an associated professor. He has been involved in several National and International research projects related to switching, multicast switching technologies, traffic engineering and Multimedia value-added services design. He is author of several papers in the fields of switching, multicast technologies and distributed systems. Since 2000 he is in charge of the development of the new Information and Communications Technologies for the Polytechnic University of Cartagena. He is regional correspondent of the Global Communications included in the IEEE Communications Magazine since 2002.

Pablo Pavón-Mariño received the Telecommunication Engineering degree in Telecommunications in 1999 from the University of Vigo (UVIGO), Spain. In 2000 he joined the Polytechnic University of Cartagena (UPCT), where he is an Associate Professor at the Department of Information Technologies and Communications. He received the PhD. degree from this University in 2004. He is involved in several National and International research projects related to optical switching and wireless networks. His research interests include switching in optical networks, and performance evaluation in optical and wireless networks.

Javier Vales-Alonso received the Telecommunications Engineering degree from the University of Vigo, Spain, in 2000 and the Ph.D. in Telecommunications from the Polytechnic University of Cartagena (UPCT), Spain, in 2005. In November 2002 he joined the UPCT where he is an Assistant Professor at the Department of Information Technologies and Communications. He has been involved in several National and International research projects related to cellular networks, optical packet switching, wireless and sensor networks and performance evaluation issues. He is author of more than 20 papers mainly in the fields of cellular and wireless communications. His current research activities are focused on pervasive computing and performance optimization in new wireless communication paradigms.