TEACHING THE FUNDAMENTALS OF TELECOMMUNICATION NETWORKS

Rui T. Valadas

University of Aveiro, Dept. of Electronics and Telecommunications, Portugal
Fax: +351-34-381941; e-mail: rv@ua.pt

Abstract: This paper addresses the teaching of the fundamentals of telecommunication networks and proposes an integrated approach that comprises the use of both analytical and simulation tools in the learning process as well as the realization of laboratory experiments to provide hands-on experience. It is claimed that life long learning of telecommunication networks has to be supported on a solid mathematical background in the areas of probability, statistics, stochastic processes and simulation. The lack of coverage of simulation issues is seen to be the main gap in available textbooks. We show through several examples how simulation can be used to enhance the teaching of the fundamentals of telecommunication networks. The integrated approach proposed in this paper will be implemented in the degree in Computers and Telematic Engineering that will start this year at the University of Aveiro.

1.- INTRODUCTION

Telecommunication networks have seen dramatic advances in recent years. At an initial stage, there was a concentration of efforts in the research of specialized problems related to the systems being brought into operation. For example, the introduction of the Ethernet local area network, in late seventies, pushed for significant research in the area of multiple access. With the increase of research activities and the diversification of technologies, the fundamentals behind the enabling techniques became progressively more clear. The basic principles of networking are nowadays well understood allowing a more structured teaching of the subject.

It is still very common to approach the teaching of telecommunication networks by an exhaustive description of existing technologies. We believe this is clearly inefficient and that the acquired knowledge rapidly gets outdated. A life long learning of telecommunication networks needs to be supported on a solid mathematical background (especially in the areas of probability, statistics and stochastic processes) that allows to integrate performance analysis aspects in the learning process. The mechanisms behind networks must be compared not only qualitatively but also quantitatively. The following citation from the preface of the book *Data Networks*, by Bertsekas and Gallager [1], clearly enlighten this idea. *Our approach to helping the reader understand the basic principles of networking is to provide a balance between the description of existing networks and the development of analytical tools. The descriptive material is used to illustrate the underlying concepts, and the analytical material is used to generate a deeper and more precise understanding of the concepts. Although the analytical material can be used to analyze the performance of various networks, we believe that its more important use is in sharpening one's conceptual and intuitive understanding of the field; that is, analysis should precede design rather than follow it.*

There are other textbooks that pursue the approach of the Bertsekas and Gallager book, e.g. [6], [7] and [10]. All of these textbooks devote one or more chapters to stochastic processes and queuing theory, the analytical tools that enable performance studies to be carried out. We strongly adhere to this philosophy. However, going further in this direction, we believe that teaching the fundamentals of telecommunication networks must also be based on simulation tools. Analysis is sometimes only possible through approximations that drive the analytical model too far away from real life. Simulation enables the use of network models closer to reality, a feature that certainly helps motivating students. It allows students to easily experiment several solutions for a specific problem and see immediately the consequences in terms of performance.

In general, the textbooks referred above lack the coverage of simulation background and its exploration through simulation based exercises. They are mainly tailored around the use of analytical tools, which reflects itself in having the examples and exercises designed to be solved by resorting exclusively to such tools. We believe that concepts can be deeply explored if there is no such restrictions in advance. In this paper we try to show how simulation can be used to enhance the teaching of the fundamentals of telecommunication networks.

Until very recently the use of network simulators in the classroom was prohibitive due to the required computational power. Network simulators could only run on expensive UNIX workstations. The dramatic increase in the computational power of PCs (and the decrease in price) has changed this situation. For example, the Department of Electronics and Telecommunications of the University of Aveiro (DETUA), has now several laboratories equipped with PCs. Network simulators can be used by students in practical lessons. Two types of simulation exercises can be envisaged: exercises designed (i) to confirm results obtained through analysis and (ii) to study complex systems where analytical results can not easily be found. At DETUA, we have selected COMNET III as the network simulator.

A laboratory component plays an important role as a complement to the teaching of the fundamentals of telecommunication networks. As in the case of PCs, networking equipment is getting sufficiently cheap to allow its use in the classroom. Laboratory lessons provide students with hands-on experience and complement theoretical and practical lessons. DETUA is setting up a laboratory to allow this component to be introduced in its degrees.

In summary, we suggest that courses teaching the fundamentals of telecommunication networks use three types of lessons: theoretical, practical (making use of a network simulator) and laboratory (using networking equipment).

As part of electrical and information engineering degrees, the fundamentals of telecommunication networks need to be complemented in several ways. Although this is beyond the scope of this paper, the main directions are worth mentioning. As a first step, the protocols that are used to implement the networking functions and the architectures that define how networking functions are organized have to be carefully studied. This can be done in parallel with a more detailed description of existing technologies (e.g. internet, ISDN, frame relay, ATM). Other issues to be covered are network security, network management, services such as e-mail or www, client-server applications and multimedia. Also, there is place for more emphasis on laboratory experiments. Suitable textbooks for this part are [4], [8] and [9].

In the following sections we detail the curricula of mathematical background, fundamentals and laboratory. Throughout the description we give several examples on how simulation can be used to complement analysis.

Some of these ideas have already been experimented in courses at DETUA. The overall approach will be implemented in the degree in Computers and Telematic Engineering that will start this year at the University of Aveiro.

2.- MATHEMATICAL BACKGROUND

In this section we discuss the required mathematical background in the areas of probability, statistics, stochastic processes and simulation. We assume that other areas traditional in electrical and information engineering degrees, such as differential and integral calculus, linear algebra and numerical analysis, are also covered.

It is important to integrate simulation topics in the teaching of probability, statistics and stochastic processes. Simulation serves to add a practical component that helps in understanding the concepts. Exercises on these topics can be based on a mathematical software package such as MATLAB.

An interesting issue to debate is whether optimization issues should also be included as part of the mathematical background. Optimization is an important tool for the design and resource management of telecommunication networks. We have the opinion that optimization fundamentals, such as linear programming, should be a part of any electrical and information engineering degree, irrespective of the approach followed in the teaching of telecommunication networks.

2.1.- Probabilities

The probability curricula can be pretty standard, based for example in chapters 1 to 3 of [5]. However, the introduction of simulation requires a detailed coverage of computer methods for generating random variables. This can be based, for example, in chapters 7 and 8 of [3]. We recommend an exercise, suggested in [3], were students need to use simultaneously the acceptance-rejection, inverse transform and composition methods to generate the beta distribution. This exercise helps students in understanding the computational efficiency issues associated with the generation of random variables. It can be solved using MATLAB.

2.2.- Statistics

Statistics is important when it comes to teaching the fundamentals of telecommunication networks for two reasons. First, students must be capable of inferring a distribution from sampled data (for example, from measurements of interarrival times of calls to a PABX or from measurements of interarrival times of packets to a local area network). Second, simulation requires the knowledge of statistical techniques for the analysis of output data.

Topics to be covered are: concepts of population and sample, descriptive statistics, point estimation, interval estimation, graphical tools for statistical inference, hypothesis tests and tests for random numbers.

Exercises on statistical inference can be easily performed with the help of MATLAB. We can explore simultaneously the computer generation of random variables (that was part of the probability curricula) and statistical inference in a first exercise where students practice statistical inference techniques on distributions generated by their own. Also, we strongly recommend an exercise for calculating the coverage of the confidence interval using distributions other than the Normal. This allows students to become aware of the severe errors that can be incurred when the underlying distribution is not Normal.

2.3.- Simulation

In terms of simulation the following topics are to be covered: simulation using a (traditional) programming language, teaching of a simulation language, initial transient detection techniques, statistical analysis for terminating and non-terminating simulations and variance reduction techniques.

Through a first exercise on the simulation of an M/M/1 queue, using the programming capabilities of MATLAB, students can learn the principles of discrete event simulation. Although a network simulator can hide the programming issues from the user, this knowledge helps in understanding the requirement for keeping the network models simple (events take time and the number of events must be kept at a minimum). A simulation language can then be taught to enable the simulation of more complex models (at DETUA we have already tried SIMSCRIPT II.5 and SIMAN/ARENA). Although this is not essential, a simulation tool can be helpful in the study of specialized models that the network simulator can not handle. Exercises around the statistic analysis of output data can be carried out using MATLAB and previous implementation of the M/M/1 model. At least the replication/deletion and the batch means methods [3] should be covered.

2.4.- Stochastic Processes

The curriculum of stochastic processes is tailored towards establishing the basic results of queuing theory. It must also provide students with basic skills for the analysis of telecommunication networks although it is not the major objective. Topics to be covered are: Markov chains (both discrete-time and continuous-time), Poisson processes, Little theorem, PASTA property, M/M/1, M/M/m, M/M/∞, M/M/m/m and M/G/1 queues. The network simulator can be used to compare the theoretical results relative to M/M/1 and M/M/m/m queues with those obtained by simulation.

3.- FUNDAMENTALS

We classify the fundamentals of Telecommunication networks as follows: error control, framing, multiplexing, multiple access, routing, flow and congestion control, ATM networks, switching and topological design. We will only cover some of these topics.

3.1.- Introduction

Teaching telecommunication networks starts by an overview covering history, basic services (connection-oriented versus connectionless), elements (links and switches) and mechanisms (multiplexing, switching, error control, flow control and resource allocation), types of networks and layering. We greatly appreciate the approach followed in chapter 2 of [10].

3.2.- Multiplexing

When studying the multiplexing function, statistical multiplexing should be compared with time division and frequency division multiplexing in terms of average delay per packet. This comparison can be carried out analytically, assuming Poisson arrivals as in [1]. Students can then extend the comparison with the help of the network simulator by considering bursty sources (for example, a 2-MMPP source), observing that additional gains can be obtained through statistical multiplexing and acquiring some basis for the understanding of ATM networks. We note that there are already theoretical results that can handle the case of bursty sources but the required mathematical background is too advanced. Simulation can be used to overcome this problem.

3.3.- Multiple Access

Multiple access gives students their first contact with mechanisms that allow the communication between more than two users. Topics to be covered are: comparison of multiple access schemes based on throughput and average delay analysis; fixed assignment (frequency division and time division), random access (ALOHA, CSMA, CSMA/CD and capture phenomena), centralized demand assignment (polling and adaptive polling), distributed demand assignment (ring protocols) and reservation schemes; discussion of desirable characteristics of multiple access schemes for high-speed local area networks; examples of local area network standards (Ethernet, Token Ring and DQDB).

The network simulator can be used to verify theoretical results on the throughput and average delay of several schemes. In addition, the simulator can be used to study IEEE 802.1 Ethernet and IEEE 802.5 Token Ring protocols without many of the assumptions that are usually taken to make analysis possible. For example, students can appreciate the results of changing the parameters of the truncated binary exponential back-off algorithm of the Ethernet protocol.

3.4.- Routing in Circuit Switched Networks

When it comes to routing most textbooks only address routing in packet switched networks. We believe that routing in circuit switched networks is also important for two reasons. First, circuit switching principles are used in ATM networks. Second, exact analytical results for the blocking performance of circuit switched networks using fixed routing can be easily derived by resorting to multi-dimensional Markov chains (not true for packet switched networks). This second feature eases the comparison of simulation and analytical results. Topics to be covered are: Erlang-B formula, Engset distribution, analysis of fixed routing through multi-dimensional Markov chains, reduced load approximation, dynamic routing protocols, evolution of the AT&T network.

With the network simulator, students can try dynamic routing protocols (where analytical results are, in general, difficult to obtain) and compare them with fixed routing in terms of blocking performance. Also, starting from a network with very high blocking and fixed routing, students can be invited to add new links to the network (where each link has a pre-assigned cost) and use better routing protocols to achieve a specified blocking probability at minimum cost. This exercise introduces a cost dimension into the teaching of telecommunication networks. Students must learn soon that their work is cost constrained.

3.5.- Routing in Packet Switched Networks

Routing in packet switched networks starts by introducing the Kleinrock approximation as a tool for calculating the average packet delay. As shown in [1], routing algorithms can be explained with the help of graph theory. Therefore, algorithms for calculating spanning trees, minimum weight spanning trees and shortest paths should be covered. Optimum routing should also be addressed to provide a reference for routing performance. With optimum routing students learn that the network must be looked as a whole if one wants to optimize its performance.

Topics to be covered are: Kleinrock approximation, network algorithms (spanning trees, minimum spanning trees, shortest paths), basic routing protocols (flooding and broadcasting, shortest path routing and optimum routing), stability problems of adaptive shortest path algorithms, network interconnection through bridges and routers as applications of spanning tree and shortest path routing, IP protocol, distance vector versus link state routing, routing in the Internet (distinction of interdomain and intradomain protocols and brief presentation of RIP, OSPF, EGP, BGP and CIDR protocols).

In terms of exercises, simulation can be used to assess the Kleinrock approximation in several situations (e.g. two equal-capacity transmission lines in tandem and a more complex network). It can also be used to compare optimum routing with shortest path and spanning tree routing. Exercises on optimum routing require the availability of an optimization routine (implementing, for example, the flow deviation algorithm) that can be provided as a MATLAB routine that students can have access to.

3.6.- ATM networks

ATM networks provide a rich field for the consolidation of many previous concepts. We favor a less traditional approach, tailored to the understanding of resource management aspects. We believe this is the way students get the most out of ATM. Topics to be covered are: cell structure, distinction between the cell level and call level of a connection (grade of service versus quality of service), quality of service parameters, service classes, distinction between the management plane and control plane (switches versus cross-connects), the virtual path concept as a tool for resource management, virtual network architectures, traffic control functions (shaping, policing, and admission control), admission control policies (peak rate versus effective bandwidths) and discussion on how virtual paths can be used to limit the signaling load on the network. We note that, for example, the specifics of AAL protocols are out of the scope of the fundamentals.

The network simulator can be used to verify how statistical multiplexing is affected by the fragmentation of resources that occurs when using virtual path connections.

3.7.- Topological design

Topological design is a subject not usually addressed as part of the fundamentals of telecommunication networks. However, this gives the student a first set of tools for planning several types of networks, bringing a new dimension to the understanding of the subject. Topics to be covered are [1], [2]: design using spanning trees, Esau-Williams algorithm, capacity assignment for continuous capacities, concentrator location and reliability issues.

In terms of exercises, we recommend the design an ATM virtual network based on virtual paths. This requires the availability of an optimization routine tailored to this specific problem which can be provided as a MATLAB routine. The whole exercise can also use MATLAB.

4.- LABORATORY

Laboratory lessons can be designed to complement most of the topics covered in previous section. We give a few examples.

(i) Students can install an Ethernet network and see the Ethernet protocol in action using a protocol analyzer. In addition, students can be asked to repair malfunctions resulting from excessive cable length or lack of 50-ohm terminations.

(ii) With a few routers and a protocol analyzer, several experiences around routing in packet switched networks can be carried out. For example, students can see how the routing tables reconfigure when there is a link breakdown and how distance vector (e.g. RIP) and link state (e.g. OSPF) protocols operate by capturing the relevant packets with the protocol analyzer.

(iii) Since most routers can also be configured as bridges, the equipment used in previous experiment can also be used to study routing using spanning trees and to see in action the protocols for installing and maintaining the spanning trees.

(iv) Bridges and/or routers can be used to solve problems resulting from excessive traffic in one or more local area networks.

We note that the main goal at this stage is not to learn how to configure and program networking equipment. Therefore, there must be carefully prepared laboratory guides that ease, as much as possible, the interface with the networking equipment and help students to concentrate on the main issues.

5.- CONCLUSIONS

This paper addressed the teaching of the fundamentals of telecommunication networks and proposed an integrated approach that comprises the use of both analytical and simulation tools in the learning process as well as the realization of laboratory experiments to provide hands-on experience. It was claimed that life long learning of telecommunication networks has to be supported on a solid mathematical background in the areas of probability, statistics, stochastic processes and simulation. While there are already several text books following this approach they lack sufficient coverage of simulation issues. We have shown, through several examples, how simulation can be used to enhance the teaching of the fundamentals of telecommunication networks. We also believe that, in general, textbooks do not cover all subjects pertaining to the fundamentals of telecommunication networks (e.g. routing in circuit switched networks and resource management of ATM networks). Laboratory exercises using networking equipment, such as routers and bridges, were also seen to play an important role at this stage. The integrated approach proposed in this paper will be implemented in the degree in Computers and Telematic Engineering that will start this year at the University of Aveiro.

References

[1] Bertsekas, D., Gallager, R., 1992, Data Networks, Prentice-Hall, 2nd edition.

[2] Kershenbaum, A., 1993, Telecommunications Network Design Algorithms, McGraw-Hill.

[3] Law, A., Kelton, D., 1992, Simulation, Modelling and Analysis, McGraw-Hill, 2nd edition.

[4] Peterson, L., Davie, B., 1996, Computer Networks: A Systems Approach, Morgan Kaufmann.

[5] Ross, S., 1997, Introduction to Probability Models, Academic Press, 6th edition.

[6] Saadawi, T., Ammar, M., Hakeem, A., 1994, Fundamentals of Telecommunication Networks, Wiley.

[7] Schwartz, M., 1987, Telecommunication Networks, Addison Wesley.

[8] Stallings, W., 1997, Data and Computer Communications, 5th edition, Prentice-Hall.

[9] Tanenbaum, A., 1996, Computer Networks, Prentice-Hall, 3rd edition.

[10] Walrand, J., Varaiya, P., 1996, High-Performance Communication Networks, Morgan Kaufmann.