

# A Networking Laboratory for the Developing World

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## ABSTRACT

Internet-based communication is assuming an increasingly important role in the developing world. It is thus crucial that students be exposed to contemporary networking equipment in a realistic setting, in order to connect theoretical material taught in lecture courses with the realities of physical hardware. To this end, a large computer networking laboratory has been set up to provide a realistic environment for teaching internetworking concepts. This laboratory provides university-level students with a testbed to experiment with fundamental issues of internetworking in a way that cannot be provided by simulators and to a degree of rigor not possible with the commonly available laboratory setups designed for technicians. We describe the motivations for setting up the laboratory, its network structure and equipment, and the type of experiments students conduct. The laboratory structure is influenced heavily by the limited funds at our disposal — a common problem in the developing world. Many of the problems we faced in setting up our equipment (such as the crucial impact of proper electrical grounding on system performance) are not ordinarily encountered in developed nations. Our experiences are thus likely to be of value to others in the developing world who are contemplating setting up experimental facilities for teaching networking.

## INTRODUCTION

We describe our experiences in setting up a large computer networking laboratory at the Department of Electrical Engineering, University of Engineering and Technology, Lahore, Pakistan. As IP-based communication starts assuming a dominant role in worldwide communications, developing nations like Pakistan need to keep up with technological developments and prepare their engineers to use this technology in the near and far future. The

graduates of our department occupy key positions in the telecommunications hierarchy of our country. We therefore need to keep our graduates fully aware of current and projected developments in communication technology. Setting up a computer networking laboratory is one of the key steps we have taken to support this objective.

The impact of IP-based communications may well be more dramatic in the developing world than in industrialized nations. This is because the existing public switched telephone network (PSTN) infrastructure in the third world is weak, unreliable, and expensive. The inherent fault tolerance and significantly low cost of IP-based packet-switched communications is thus a welcome alternative to the traditional circuit-switched PSTN infrastructure. At the present time in Pakistan, the traditional PSTN coexists with a contemporary IP network. As we shall describe in the remainder of this article, our laboratory is designed to realistically model this hybrid (PSTN+IP) network architecture.

Our experiences in setting up and running this laboratory are of obvious relevance to the readers of this magazine who belong to the developing world. At the same time, they highlight the issues professionals in the industrialized nations need to consider when setting up such facilities in the third world. Our laboratory can serve as a model in situations where adequate funds are available for setting up a comprehensive facility in a large department. Where a smaller facility is desired, portions of our laboratory can serve as models. For example, we simulate three “cities” in our laboratory, each with three layers of routers. Others might wish to simulate fewer cities with, say, two layers of routers. The guidelines we followed in selecting and installing equipment in our laboratory are of relevance to readers in the developing world, regardless of the extent to which they replicate the architecture of our laboratory.

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This article is organized as follows. The following section outlines the financial, organizational, and technical constraints under which we worked. This is followed by a section that details the structure of the laboratory. We describe the hardware and software installed in the laboratory. One of the most critical issues when installing telecommunications equipment in the developing world is the lack of electrical standards. Our experiences in this regard are described later.

Merely setting up a laboratory and furnishing it with equipment is worthless unless a body of teaching material is written and refined over many years. We outline the material we are developing for the laboratory. We present our conclusions and future plans.

### CONSTRAINTS

The Department of Electrical Engineering at the University of Engineering and Technology-Lahore is very large, with 1100 undergraduate and 400 graduate students. Most of the undergraduates take a course in computer networks in their final (senior) year and are thus potential users of our laboratory. The approximately 240 students in the networks course are split into four sections of about 60 students each. The laboratory is thus designed to comfortably accommodate 60 students at a time.

Our laboratory was set up with a one-time grant of Rs. 10,000,000 (US \$170,000) from the government of Punjab. Although this is a generous amount by our standards, it did not permit us to consider certain classes of equipment, such as an asynchronous transfer mode (ATM) network. Furthermore, the equipment we did obtain is not replicated in numbers that would make it possible for each student to work alone on, say, a single router, as would be the case in the United States or Europe.

Our overall budget was broken up roughly as shown in Table 1. It is important to note that we already had a large laboratory space available to us, so no building construction costs are included. Furthermore, as we are a large department and need to accommodate 60 students in each laboratory session, the fraction of the budget allocated to workstations (20 percent) is large, despite the fact that these are shared by two students each during normal circumstances.

A significant 40 percent of the budget is allocated to routers and their accessories. We expect that routers will consume a major portion of the budget of any computer networking laboratory. Uninterruptible power supplies (UPSs) are necessary to guard against power failure in most third world countries, and we recommend that no compromises be made in this category. Online UPSs (those that isolate equipment from the mains power supply at all times) are expensive and should be used for costly equipment like routers and switches. Offline UPSs only cut in when there is a power failure, are cheaper, and can be used with less expensive equipment like workstations (in our case commodity PCs).

The lack of staff trained in maintaining such a laboratory posed a serious challenge. At the present time, this laboratory is being managed



Figure 1. The computer communication laboratory.

Category	Budget fraction
Routers and accessories	40%
Workstations	20%
Uninterruptible power supplies	10%
Modems Radio and dial-up	10%
Infrastructure Air conditioning Furniture Wiring Earthing (grounding)	10%
Switches and hubs	5%
Telephony equipment PABXes, faxes, phone sets	5%

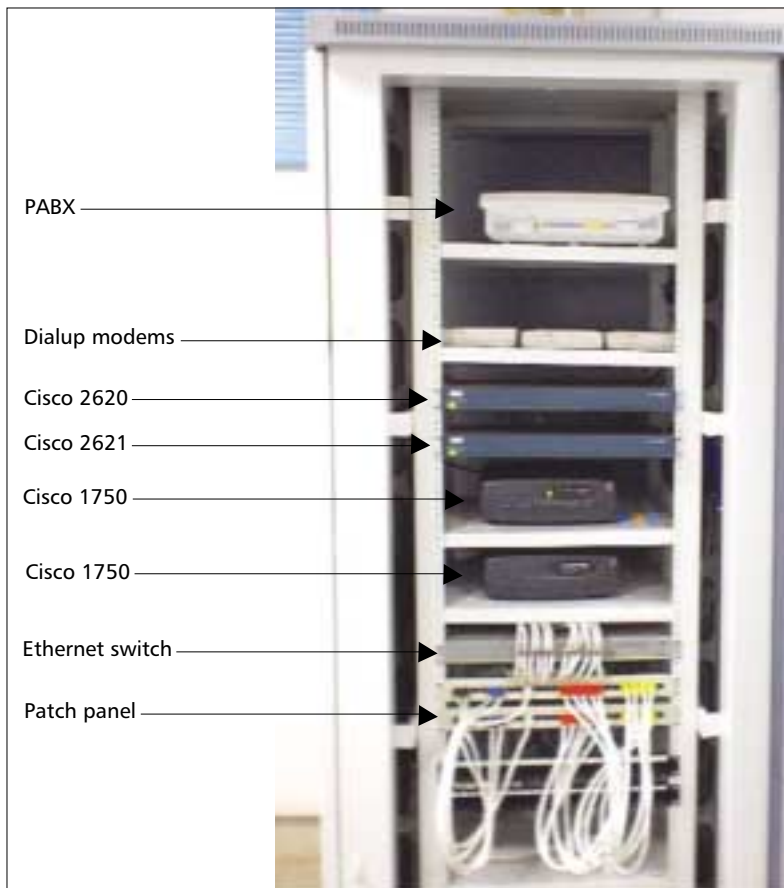
Table 1. Breakup of the cost of the laboratory.

by students who voluntarily offer their time to keep it operational.

While setting up the laboratory we discovered that the technical support personnel available in the local market were not fully aware of IEEE networking standards. A lot of effort was needed to train contractors to follow international standards of network wiring, power distribution, and equipment installation. One of the major issues that delayed the operation of the laboratory was improper power distribution, unbalanced neutral and ground voltages, and nonexistent earthing (grounding) at the distribution transformer and distribution box of the laboratory. This is discussed later.

### THE STRUCTURE OF THE LABORATORY

The infrastructure of the laboratory was designed to simulate a nationwide network connecting three cities with different types of physical communications links. Three nodes, each



■ **Figure 2.** One of the three equipment cabinets in the laboratory.

housed in a full-height cabinet, represent three cities (named after the main cities of Pakistan) and are almost identical as far as equipment is concerned. By keeping the nodes identical we permit all students to perform the same experiments at the same time, simplifying administrative effort for the instructors. The interconnections between these virtual cities is slightly asymmetric, permitting interesting routing phenomena to be demonstrated. Figure 1 shows a photograph of the laboratory, Fig. 2 one of the cabinets.

Considerable effort was expended in making the network of the laboratory (Fig. 3) look as much as possible like the structure of a real nationwide network. The first step in this direction was to adopt a layered structure. Each simulated city has three layers, A, B, and C, that correspond to the core, distribution, and user layers generally used in industry.

#### TOP LAYER (A)

This layer mostly consists of high-speed links and powerful routers to accommodate the load of the lower layers. In real life the majority of top-tier data network operators (DNOPs) interconnect with each other in this layer. From an administrative point of view, the administrators of lower-layer DNOPs cannot enforce policy issues on this layer; they have to accept whatever is offered. This layer comprises Cisco 2620 routers. These routers are connected directly as well as via other media (e.g., microwave links).

This gives us a degree of asymmetry in connectivity that is interesting from a routing point of view.

#### MIDDLE LAYER (B)

Layer B acts as an intermediate layer and provides connectivity between the lower layer and the backbone. The routers on this layer can be considered regional nodes and can permit a regional DNOP to implement routing policies of its choosing.

This layer comprises Cisco 2621 routers that have both Foreign Exchange Station (FXS) and Foreign Exchange Office (FXO) modules installed in them. FXS modules connect to a telephone/fax or private automatic branch exchange (PABX) and generate suitable telephone signals. FXO modules are designed to be connected to the PSTN. In our laboratory we simulate the PSTN with small PABXes.

At the present time the 2621 routers communicate with each other through the upper-layer 2620 routers. We plan, in the future, to get fiber optic equipment and connect all the layer A 2620 routers through a fiber backbone. When this happens, we will interconnect the layer B 2621s through high-speed links to create a multi-layer backbone. Until then, we have the capability to connect the 2621s via Ethernet to simulate a backbone should the need arise.

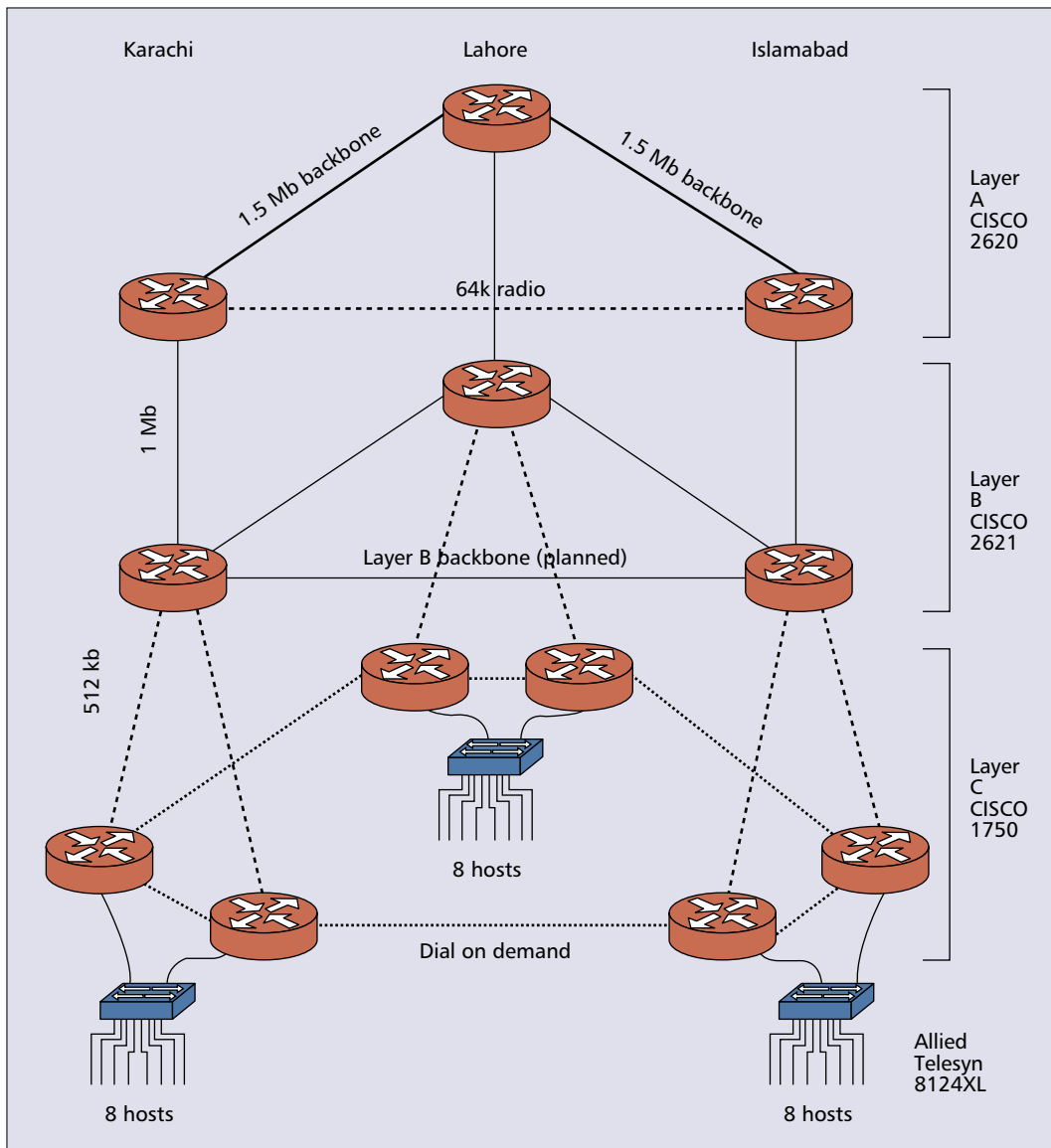
#### BOTTOM LAYER (C)

This layer comprises all leaf users. There are two Cisco 1750 routers available at this layer. The 1750 routers do not communicate with each other directly; they do so only through the 2621 routers of layer B. Students can be permitted unsupervised access to the routers of this layer, as any misconfiguration of these routers has very limited impact on the laboratory as a whole.

The three PABXes in each city can be interconnected to form a small but realistic PSTN. This permits students to compare the voice quality available on a packet-switched voice over IP (VoIP) network against a circuit-switched PSTN at varying levels of traffic. In many developing nations part of IP communications takes place over the PSTN, so this is a useful facility for our students. We use our own PABXs rather than our university's central telephone exchange for security reasons, as we wish to keep our laboratory completely isolated from the outside world. This isolation keeps any errant experiments from interfering with the real Internet. It also protects our laboratory from the unwelcome attention of outside hackers.

### HARDWARE AND SOFTWARE

In this section we describe the hardware and software choices made during the setting up of the laboratory. For hardware the overriding consideration in a developing nation is the issue of technical support. Equipment like routers, radio modems, and switches is expensive but not costly enough to justify a technician flying in from overseas for emergency repairs (as was the case for the mainframe computers of the '60s and '70s). Thus, whatever is acquired must be backed up by maintenance support, preferably in-city.



■ **Figure 3.** The network structure of the laboratory.

Considerable effort was expended in making the network of the laboratory look as much as possible like the structure of a real nationwide network. The first step in this direction was to adopt a layered structure.

At the time we were designing the laboratory (2000), Cisco was the major player in the router market in Pakistan, with a large fraction of the market share and extensive technical support. At the present time many other companies have entered the field, and a new laboratory being designed today could, in addition to Cisco, choose from 3Com, Alcatel, Allied Telesyn, Huawei, and Motorola, among others. Another important consideration for choosing Cisco routers was that most potential employers were using Cisco equipment, so students trained on these would be in great demand. Similar considerations applied to the other equipment discussed below.

### ROUTERS

The routers chosen for this laboratory are the Cisco 2620, 2621, and 1750. All of these routers are modular; that is, they have plug-in modules that can be replaced as the need arises (so, e.g., one may replace an Ethernet port with a Gigabit Ethernet port.) This is an important considera-

tion for future expansion and modification of our laboratory.

### SWITCH

An Allied-Telesyn model AT-8124XL Fast Ethernet switch is installed in each cabinet and can be used for virtual LAN (VLAN) experiments. In addition to introducing VLAN technology to our students, these switches reduce the cost of our network experiments, as each can simulate multiple switches that would be distributed over a real-world organization.

### RADIO MODEM

Radio modems operating on the unlicensed frequency band (2300–2400 MHz) are very popular for data networking in the third world as well as rural areas of the industrialized world, where existing copper infrastructure is poor and unreliable for last mile connectivity. We have installed two Aircom Airlink S-band radio modems in two of our cities. Managing these modems is a useful exercise for students.



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In the third world, these kinds of radios are popular for intracity data links of up to 40 km. In our laboratory, however, we use them to simulate intercity microwave links.

The wireless link provided by these modems reduces the hop count between Islamabad and Karachi by one (Fig. 3). We can set up our routing algorithm to use this link as the preferred path between these two cities. However, as the capacity of the radio link (64 kb/s) is far less than the capacity of the alternate 1.5 Mb/s path, the routing algorithm switches over to the alternate path when the radio modems saturate. This experiment vividly illustrates the behavior of routing algorithms under load conditions.

#### DIALUP MODEMS AND PABXs

We have added dialup modems to our lower layer to simulate automatic dialup connections between routers in case of loss of backbone connectivity. This is an important consideration in the developing world, and illustrates to students how the PSTN and IP networks coexist at the present time. The PABXs and dialup modems allow students to experiment with "dial backup" schemes. This equipment can also be used to simulate a model Internet service provider (ISP) setup.

#### PATCH PANELS

Patch panels (bottom of Fig. 2) save wear and tear on ports of expensive switches and routers because of repeated plugging and unplugging of connectors. It is standard practice to terminate the most frequently used ports on patch panels. We have terminated each and every port of every piece of equipment on these patch panels. This permits us to rewire the entire laboratory without disturbing any expensive equipment.

#### HOSTS

We have 44 Intel PIII (733 MHz) PCs in our laboratory to act as hosts. They have 256 Mbytes RAM and 20-Gbyte hard disks. These machines have the Intel 815e motherboard but are otherwise unbranded. The machines are assembled within Pakistan from mostly imported parts, although casings and such are locally made. Such machines perform well, and are cheaply maintained and repaired. Use of such unbranded machines results in large cost savings. Furthermore, such machines can be freely opened, modified, and reconfigured, something that is not possible in most branded systems.

#### LINUX OPERATING SYSTEM

Our laboratory is completely Linux-based. This is because of its stability, reliability, and low cost, and our extensive prior experience with this operating system [1, 2]. All networking functions are freely available for this operating system; in addition, a wide range of free software is available for it through the Gnu project. Students trained on Linux are comfortable with other variants of UNIX as well as Solaris. Finally, Linux is commonly used by ISPs and other potential employers of our students in Pakistan. Those with more lavish budgets may wish to consider Microsoft Windows

in addition to or instead of Linux. However, the operating system that is prevalent in commercial networking applications in a specific country must always be the primary teaching platform.

### ELECTRICAL CONSIDERATIONS

A number of issues related to electrical power distribution and grounding (earthing) have to be considered carefully when installing communication equipment in the third world. While there are strict standards regarding these issues in the developed world, we have had to contend with missing or unenforced rules. As the equipment being installed was expensive, and subject to malfunction and damage because of poor electrical wiring, we were especially careful regarding this area. We knew potential problems might exist because of our prior experience. For example, we knew of the following scenarios, which we believe to be common in the third world.

◊ A violent thunderstorm caused a lightning strike on one of our university residence halls. Because of poor earthing a number of hubs, LAN cards, and modems were destroyed. In a similar incident several computers were burned out, fortunately without injury to any individual.

◊ In one of our computer laboratories, computers that were switched off would sometimes decline to switch on again. Sometimes, but not always, this problem could be solved by shorting the pins of the power connector. An investigation discovered that the ground-to-neutral voltage was alarmingly high. In this case, even the installation of a separate ground for the laboratory did not solve the problem. It was ultimately discovered that the problem lay in the power being supplied by the electric company and could only be solved by properly grounding the supply transformer outside the building.

The consequences of improper grounding for computer and communications equipment involve complex phenomena ([3], Ch. 2) that deserve careful consideration. Developing nations can ill afford the expensive damage that can result from ignoring these issues.

#### PLACEMENT OF AIR CONDITIONERS AND FANS

Air conditioning (AC) and fans are essential in the hot climates found in most of the developing world. Central AC cannot be afforded by financially constrained state institutions such as ours. We thus have to rely on wall mounted ACs and have four units in our laboratory. In addition, we also use wall mounted fans for particularly hot days.

The electromagnetic interference (EMI) generated by ACs and fans needs to be considered carefully when locating this equipment. In particular, ACs generate huge amounts of EMI when they switch on and off in response to thermostatic signals. Prior experience in Pakistan has revealed that placing ACs close to routers and copper communication cables can result in significant interference problems with resultant errors and malfunctions.

We placed our AC units as far away from the

cabinets housing our routers as was practicable, even though this resulted in suboptimal cooling, as the ACs were exposed to direct sunlight. Furthermore, the cabinets themselves were placed 1 m away from the nearest walls and as far away from reinforced concrete (RC) beams as possible. RC beams have steel rods embedded in them, which can channel EMI in subtle and unexpected ways.

### WIRING AND POWER SUPPLIES

We tried to keep the power supply cables and data cables as far away from each other as possible. Despite higher cost, we used shielded twisted pair (STP) wire instead of unshielded twisted pair (UTP), since experimentation revealed that STP resulted in a 10 percent improvement in bandwidth.

Power failures are common in the developing world, and most ISPs use elaborate backup systems. In our case we chose to provide a 20 min backup for all computers and a 2 h backup for the routers using UPSs. This is because:

- Anything more elaborate would have been outside our budget.
- We are not a commercial organization supplying network services to outside customers.
- Our university has mechanisms for switching to alternate sources within a few minutes in case of a power failure.

We use offline UPSs for our computers and online UPSs for routers and other expensive equipment. Computers can happily tolerate the somewhat poorer quality power provided by the cheaper offline UPSs. Routers, switches, radio modems, and so on benefit from the “cleaner” power provided by substantially more expensive online UPSs.

## EXPERIMENTS

Our students carry out a number of experiments during 18 laboratory sessions of 2 h each. The topics covered are described below. We have experience with most of the popular textbooks on computer networking, such as Comer [4], Peterson and Davie [5], Stallings [6], and Tanenbaum [7] for our lecture course. We are currently using Kurose-Ross [8] and find its top-down approach useful in motivating student interest. For example, we start our students off with Java network programming very early in the course (we use Java as our primary teaching language, so this is easy for us). The material covered in laboratory sessions is easily transported to students’ home machines, and many students enthusiastically run client-server applications between their homes or dormitory rooms. The Ethereal Network Analyzer ([www.ethereal.com](http://www.ethereal.com)) is a major tool in later experiments. Versions of this powerful but free software can be loaded by students into their personal machines (or into shared machines set up for them elsewhere in the university), thus creating further opportunities for learning and reinforcement of laboratory material.

In the following, we describe the concepts covered by our experiments in a top-down fashion. The introductory material in each layer is

covered in the first half of the course, while the remaining topics are covered in the second half once students have had a chance to develop some sophistication.

### APPLICATION LAYER

- Introductory problems in Java network programming
  - Basic concepts of client-server programming using TCP and UDP
  - Introduction to Ethereal as an analysis tool
  - Using Ethereal to analyze the behavior of HTTP, FTP, telnet, SMTP, POP, and DNS
- Domain Name Service (DNS), in our opinion, deserves the greatest attention due to its centrality to the Internet. Discussion of *mail servers* is also important since most students use Web-based email (e.g., Yahoo or Hotmail) and are thus ignorant of the ramifications of SMTP and POP.

**VoIP** — The laboratory supports full VoIP equipment, permitting us to conduct many interesting experiments. It is important for us to prepare our students for a future in which most telephony will be over IP. Many corporations in Pakistan and other developing nations already use VoIP over their internal networks.

There are a number of possibilities to experiment with VoIP in our laboratory. Some of the routers have H.323-based voice interface cards (VICs). We also have Session Initiation Protocol (SIP) based hardware that can be installed in some of the host computers. Finally, we can also use H.323-based Gnomemeeting ([www.gnomemeeting.org](http://www.gnomemeeting.org)) on our Linux machines.

Some of our students have developed Linux-based VoIP solutions using hardware cards [9]. This approach can be contrasted with software-based approaches and the facilities available on the routers.

**Security** — Here we provide an introduction to security issues, such as how an unencrypted password can be captured using a sniffer, the importance of using ssh or equivalent for logging on, using access lists to block access, and low-cost firewalls implemented with Linux. It is regrettably all too easy to provide students with details of recent security breaches from the daily press.

### TRANSPORT LAYER

- Capture a TCP/UDP segment and dissect its contents.
- Capture and study a TCP three-way handshake and termination.
- Observe fragmentation of TCP segments: one link in a specific path is set to have a low MTU. Students are required to show fragmentation taking place.
- Observe TCP flow control.
- Observe the impact of TCP congestion control by increasing traffic between two end systems.

### NETWORK LAYER

- Check if a target computer is alive using ping.
- Interpret the output of ping.
- Use netstat on your host machine.

*The lab supports full VoIP equipment, permitting us to conduct many interesting experiments. It is important for us to prepare our students for a future in which most telephony will be over IP.*

Commercially available network management systems, such as Cisco Works, are beyond our financial resources. We have, however, developed a Java-based Network management system based on SNMP that can be used to introduce students to this area.

**Traceroute** — List the path taken by a packet from source to destination. Justify why a specific path is being followed. The laboratory administrator sets up a static path, and students are required to trace it and compare it with the dynamic path used earlier. Note the delays between various cities in the network. This material can be usefully augmented by homework assignments in which students are challenged to find the most distant host computer from their PCs (in terms of hops, time delays, or geographical distance). Also covered are dissecting RIP broadcasts and analyzing Open Shortest Path First (OSPF) messages.

Students log into a router and use IOS to investigate its characteristics (amount of memory, etc.), investigate the processes that are running, look at the status of all interfaces, and study the status (load, queuing strategy, I/O packet drops, I/O errors) of each router in a city in detail. This is repeated under different load conditions. They use extended access lists to control access to a router, and verify that their configurations work as expected.

**Dial on Demand Routing (DDR)** — This is a cost-effective solution when we want to provide backup support for a network, if traffic is limited, if email only access is required, and in situations where real IP connectivity is not yet set up. DDR is of great relevance to the developing world, where Internet connectivity is nonuniform. In Pakistan small businesses use DDR extensively.

**Network Management Systems** — Commercially available network management systems, such as Cisco Works, are beyond our financial resources. We have, however, developed a Java-based network management system based on Simple Network Management Protocol (SNMP) to introduce students to this area.

#### DATA LINK LAYER

- Analysis of Ethernet frames
- Analysis of ARP messages

#### PHYSICAL LAYER

This is perhaps the most interesting topic from the electrical engineer's point of view, and an area where our students can differentiate themselves from computer science and information technology graduates. Topics include the waveforms used in various parts of the system (Ethernet ports, etc.) and the effect of externally applied noise on the error rate in a data link.

### CONCLUSIONS AND FUTURE PLANS

The multiyear time period required to set up this laboratory is but a beginning. Developing and writing up experiments to be performed by students is an onerous task that takes up a significant amount of instructors' time. By design, the laboratory has a rich complement of equipment that can permit dozens of interesting experiments that develop student interest in networking technology. However, it will be some time before we can get around to developing experiments for all the available equipment.

The laboratory has already encouraged many students to carry out interesting research projects on VoIP [9] and the Linux router [10]. Although we planned the laboratory to be a resource for undergraduate students, we have found it to be of interest and value to Master's students as well. A recent graduate level course was enthusiastically received, although it did require greater effort to develop experiments at a more sophisticated level.

Finances and human resources permitting, our future plans call for the augmentation of this laboratory with:

**Fiber optic links.** These will permit demonstration of and experimentation with high-speed links. Students will be able to experiment with extremely high-bandwidth data transfers and observe the performance of the routers under these stressful conditions. Our plan is to acquire multikilometer spools of fiber so that latencies can be realistically experienced.

**A live VSAT connection from one cabinet to another.** This will permit us to experiment with the contrasting bandwidths and latencies of VSAT connections and fiber optic or copper links.

**Wireless networking.** This technology is slowly gathering momentum in the developing world; it behooves us to keep our students abreast of its developments.

For the first two items above, finances are the major concern. For the VSAT connection, in addition to funds we need to be absolutely sure about the electrical safety of external satellite dishes.

Wireless networking is a major pedagogical challenge for us since we are a state university in the developing world, and few, if any, students can afford laptops or PDAs. Thus, wireless networking needs to be demonstrated with a few university-owned devices. This is in contrast to more affluent institutions, where merely the provision of a few wireless access points will encourage students to utilize and experiment with this technology using their personal equipment.

#### ACKNOWLEDGMENTS

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## BIOGRAPHIES

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*Wireless networking  
is a major  
challenge for us  
since we are a  
state university in  
the developing  
world and few, if  
any, students can  
afford laptops  
or PDAs.*