Experience in Teaching a Graduate Course in Mobile Computing

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Abstract— **The need for "information anywhere anytime" has been a driving force for the increasing growth in Web and Internet technology, wireless communication, and portable computing devices. The field of mobile computing is the merger of these advances in computing and communication with the aim of providing seamless and ubiquitous computing environment for mobile users. Mobile computing environments are characterized by severe resource constraints and frequent changes in operating conditions. This has motivated research in many challenging problems which span several areas of computer science, computer engineering and electrical engineering, such as network protocols to support mobility, efficient and adaptive resource management techniques for wireless bandwidth and battery power, predicting mobility patterns, performance modeling and simulation of mobile applications, and supporting mobile real-time multimedia applications.**

This paper describes the experience of the authors in designing and teaching a senior/graduate level mobile computing course at Colorado State University. This course was designed for students in computer science, electrical engineering and computer engineering. The goal was to provide an in-depth understanding of the fundamental problems in the area of mobile computing and present the existing and proposed solutions for these problems from both research and development perspectives. In addition to regular homeworks and exams, students did term projects/papers to explore topics of their interest in more depth. Several mid-term and end-of-semester evaluations were done to gauge student satisfaction and short-comings of the course. These evaluations were very positive. Many students found the breadth of the information provided in the class very stimulating. Some students mentioned that they would have liked a course textbook along with the course material.

I. INTRODUCTION

The combination of wireless communication infrastructure and portable computing devices has laid the foundation for a new network computing paradigm, called *mobile computing*, which allows the users access information and collaborate with others while on the move [1]. Wireless mobile networks are typically characterized by severe constraints on resources, such as bandwidth and battery power, and by rapid fluctuations in availability of these resources; this makes it difficult for the system software to provide guaranteed quality-of-service at levels required by many distributed and collaborative applications. Also, due to mobility of the clients or the users, users may be disconnected from the network often and the users may also voluntarily switch off to save battery power; thus, management of this disconnection is a critical issue in designing mobile networks. Further, user mobility adds a new dimension to the distributed operating systems which has implications for specification, design, verification, and implementation of both system and application software [2]. A challenging issue is to determine the interface and the guarantees that the system software must provide to the developers of both location-independent and location-dependent (context-aware) [3] applications on mobile networks [4]. This has resulted in research on adaptive applications and system software which can gracefully respond to changes in operating conditions [5].

There are several articles which have identified the fundamental challenges in mobile computing [6], [7], [8]. Figure 1 provides a one line summary of these articles. Mobile systems are i) resource poor ii) less secure iii) have poor connectivity to the wired infrastructure and iv) have less energy since they are powered by battery. In order to deal with these characteristics the mobile systems should employ dynamic adaptation schemes. One of the implication is that the solutions developed for mobile systems should be interoperable since as mobile clients move one domain to another they should be able to operate in the new domain.

Mobile computing is multidisciplinary in nature, it involves many issues in computer science and electrical engineering. Currently, industry is involved in development of technology and products to support mobile communication and computing. There are several technological problems that are yet to be solved to exploit the full potential of mobile computing; many of those issues are being studied in the laboratories. Software as well as hardware engineers need be acquainted with those techniques to successfully meet the challenges of the future. There is a need to develop educational materials and curricula that incorporate newly created fundamental engineering and computer and information science knowledge in mobile computing. This will help to enhance the education and careers of future engineers and scientists by enabling them to compete in the global environment.

At Colorado State University, we took up this task to develop a research and teaching program in mobile computing. We have designed and taught a course on mobile computing that is targeted towards first year graduate students and undergraduate seniors. Several topics including wireless communication and multiple access techniques, cellular and mobile ad hoc networks, location management and mobility tracking location-aware information services, unicast and multi-casting routing in mobile networks, energy-efficient data dissemination and management, disconnected operation, mobile client-server computing and mobile agents were covered in this course. These topics provided a balanced mix of issues involved in mobile and wireless networking, operating systems and middle-ware, and application design and development. The course prerequisite was kept at a minimum to accommodate students with different backgrounds and preparation. Due to lack of any textbook in mobile computing,

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$$\text{Mobile Systems} \Rightarrow \left.\begin{array}{l} 1.\text{Resource Poor} \\ 2.\text{Less Secure} \\ 3.\text{Poor Connectivity} \\ 4.\text{Less Energy} \end{array}\right\} \Rightarrow \text{Dynamic Adaptation} \Rightarrow \text{Interoperability.}$$

Fig. 1. Mobile Computing

most of the reading materials were drawn from magazine articles and research papers.

In the following we describe the Goal and Philosophy of the course in Section II. In Section III, we describe what challenges we faced in teaching this course. The course outline along with reference to the topics covered in the course is provided in Section IV. We describe some sample homeworks and examination questions in Section V. Course evaluation and achievements are described in Section VI. Finally we provide some conclusions in Section VII.

II. Goals and Philosophy

The main goal of the course was to provide an introduction to the fundamental problems in mobile computing to graduate students in computer science and computer engineering. We wanted the students to acquire skills and knowledge which would help them towards acquiring jobs in this area as well as pursue further research. We wanted a healthy mix of technological and research issues in the course. Mobile computing is multidisciplinary by nature. We wanted this course to suitable for students with both computer engineering and computer science background; we enforced only minimal requirements on the students. We decided on an undergraduate course in operating systems to be the prerequisite. The rational was that usually operating systems course deal with several issues which need to be revisited in mobile computing environment such as resource allocation in multiuser environment, interface to assist in application development, scheduling algorithms, predicting program behavior through using past history, exploiting locality to enhance performance etc.

There are two ways in which Mobile Computing topics can be incorporated into Graduate Curriculum i) offer specialized course ii) enhance exiting courses with mobile computing topics. We adopted the first approach since it gives students an opportunity to look at different aspects of mobile systems in a single course. Further, it will help us in identifying the most efficient way of integrating the mobile computing topics into different courses in the long term.

III. Challenges

We faced several challenges in designing this course. Mobile computing is a new and evolving area. Although, there are several books in the market on mobile computing, we found none to be a suitable textbook for a introductory graduate level course which covers several aspects of mobility such as operating systems, mobile communication, and software engineering. Either these books are a collection of papers [1] or they focus only on one aspect such as mobile communication [9] or database management [10]. Asking students to buy several books was not an option; some of them are expensive. Further, the relevant papers

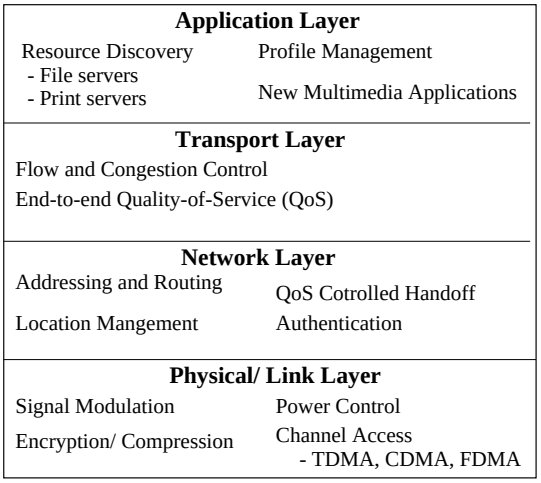

Fig. 2. Challenges in Mobile Computing

on various aspects of mobile computing are published in wide variety of journals and conference proceedings. Mobile computing courses are offered at different universities. However, we found that these courses mainly emphasize one aspect of mobile computing, namely mobile and wireless communication.

Another challenge was the choice of topics to be covered in the course. As can be seen from Figure 2, there are several issues presented by mobile computing at different layers in the system. Covering all of them in sufficient details in a one semester course was not feasible. Hence, we needed to select a substantial subset of the topics for the course. We decided to restrict the course to topics in upper three layers. Furthermore, we left out the topics on QoS and multimedia applications in mobile environment for which there are no concrete solutions currently available.

IV. Course Outline

The course outline was designed to meet our goals and the challenges. In this course we covered the following topics:

1. *Introduction to Mobile Computing* (1 Week):

(a) Rationale: Students should get an overview of the entire spectrum of mobile computing at the very beginning; they should have an understanding of the breadth of the issues involved. The primary thing to convey here is that mobile computing is more than just wireless mobile communication. The interest in mobile computing lies in the new applications which will be developed on mobile computing platforms.

(b) Topics: Nature of mobile networks, differences between distributed computing and mobile computing, applications of mobile computing, types of mobile networks (cellular, ad hoc etc.).

(c) Reference Material: Chapter 1 of Korth's book [1] provides a good overview of mobile computing issues.

2. *State-of-Art in Mobile Communication and Systems* (2 Weeks):
(a) Rationale: Covering the current state-of-art early in the course helps in identifying what is currently feasible i.e. what kind of mobile systems can be designed using current technology. This helps in identifying the research problems as well as help students who want to do implementation oriented projects to start exploring available technology early.
(b) Topics: Mobile IP [11], Jini, Mobile ATM, Wireless Access Protocol, Bluetooth.
(c) Reference Material: The book by Schiller [9] provides adequate coverage of these topics.
3. *Location Management* (2 Weeks):
(a) Rationale: Efficient location management is one of the fundamental issues in building mobile computing systems. This topic is rich in both industrial solutions and theoretical appealing solutions. Hence, this topic provides a good transition between technical issues to research challenges. Further, it shows the interaction between static infrastructure and mobile hosts.
(b) Topics: Location management in Mobile IP, PCS networks, Tradeoff between search and update cost, handoff in cellular systems. Adaptive location management, Hierarchical location management.
(c) Reference Material: Chapter 20 of Gibson's book [12].
4. *Data Dissemination/Wireless Publishing* (2 Weeks):
(a) Rationale: Data dissemination based services are appearing in the market and hence this topic provides a concrete application of mobile computing. There exist different solutions to organize data broadcast. These include scheduling and indexing techniques to optimize access time and optimize use of limited wireless bandwidth.
(b) Topics: Push based and Pull based services, broadcast scheduling algorithms for symmetric and asymmetric environments, energy-efficient indexing.
(c) Reference Material: Ch. 11 of Korth's book [1].
5. *Unicast/Multicast Routing* (2 Weeks):
(a) Rationale: Due to mobility of routing nodes the topology of the network changes frequently. Numerous unicast and multicast routing protocols have been developed efficiently deliver packets to single or multiple destinations. These protocols enable traditional distributed applications to be ported onto a mobile computing system.
(b) Topics: Connection-rerouting for connection-oriented communication, unicast and multicast protocols in mobile ad hoc networks.
(c) Reference Material: Royer and Toh's article provides survey of 8 routing protocols designed for mobile ad hoc networks [13]. Acharya and Badrinath's article provides a framework for multicast routing in mobile networks [14]
6. *Client-Server Computing and Database Management* (2 Weeks):
(a) Rationale: Mobile clients can be disconnected from the network for extended period of time. This has resulted in techniques for disconnection management in client-server based distributed applications e.g distributed databases and distributed file systems.
(b) Topics: Disconnection management, Caching and prefetching, Data replication, transaction management.
(c) Reference Material: A survey of mobile client-server computing is provided in [15]. The book by Pitoura and Samaras [10] covers data management issues in mobile computing environments.
7. *Mobile Agents* (1 Week):
(a) Rationale: Mobile agents provide a novel solution for addressing disconnections and poor connectivity in wireless networks.
(b) Topics: Security and privacy issues, applications of mobile agents.
(c) Reference Material: Chapters 1 and 2 of Cockayne and Zyda's book [16].
8. *Location-Aware/Context-Dependent Applications* (2 Weeks):
(a) Rationale: Location-aware and context dependent applications are new types of applications made possible by mobile networking.
(b) Topics: examples of location-aware and context-dependent application, frameworks for building location-aware applications.
(c) Reference Material: context-aware applications [17], [3], [18],
9. *Modeling and Simulation of Mobile Systems* (2 Weeks): Mobility models.
(a) Rationale: Performance evaluation of mobile systems involves modeling of mobility patterns of different users and time varying characteristics of wireless channels. The main goal of evaluation is how the system adapts to the increase in mobility rate. Modeling and simulation of mobility gives a deeper understanding of working of mobile systems.
(b) Topics: Mobility modeling, performance metrics, simulation techniques.
(c) Reference Material: Mobility and traffic models [19], simulation architecture [20].

V. Homeworks, Exams, and Projects:

Since we could not find an appropriate textbook on mobile computing that satisfied our needs, we did not have any available sets of homeworks and exams for our ready use. We designed homeworks and examination problems to hone and test various research and development skills as well as help us gauge understanding of the students. We describe below some of the assignments that we used in our offering of the course.

A. Homeworks and Programming Assignments

Following are some sample homeworks and programming assignments used in this course.
1. In the class, we have covered papers on fundamental challenges in mobile computing. This homework asks you to conjure new applications of mobile computing that will challenge the mobile computing community with new technologies or visionary applications. Write a short paper to describe your application/ technological advance. The paper should provide stimulating ideas or visions that may open up exciting avenues of mobile computing research. The paper will be evaluated on novelty and details of ideas. Hence it is essential to propose something new and exciting. The main purpose of the paper is to exercise your imagination. Write the paper in technical style with figures and proper references. Also make sure that the paper is technically sound and readable. Include some possible scenarios in which

the proposed application or technology can be used. You can base your paper on any existing ideas you may have come across in news or during web surfing and would have found it applicable to meet some fundamental challenges in mobile computing and or make some new applications of mobile computing possible. You can also propose application of new technology/theory to mobile computing e.g. some techniques from AI/control theory to say intelligent caching of information or to deal with security problem in mobile computing.

2. Write a simulator using CSIM for simulating Adaptive Location Management Strategy for Mobile IP with the purpose of verifying the results presented in the paper. Submit a report on the design of your simulator along with documented simulation code. In your report, also describe the experiments you conducted and present the results in the form of graphs. Explain any discrepancy you notice between the results presented in the paper and obtained from your simulator.

3. Data caching is a standard technique for minimizing access time. Consider the following technique in which a mobile host (MH) uses the on-demand channel to fetch a data item x if it does not have a cache (or local) copy. The MSS keeps track of the MHs which have a copy of data item x. Whenever the value of x changes the MSS sends an invalidation message to every mobile client which has a copy of x and makes the set of MH with copy of x to be null. On receiving the invalidation message the mobile client invalidates (throws away) its local copy of x. Compare this scheme with the data broadcasting scheme with respect to energy-efficiency, scalability, and access time taking into account the demand frequency and update frequency for the data items. State all your assumptions clearly.

Following is a general question to gauge perceptive understanding of the students:

- In the paper "Mobile Users: To Update or not to Update", the authors described the trade-off between search cost and update cost in tracking mobile users. With respect to each of the following topics discussed in the class briefly describe any interesting trade-offs involved. If you think there are no interesting trade-offs for a particular topic then say so.
  - Information Broadcasting
  - Routing in AdHoc networks
  - Causal Ordering for mobile hosts
  - Channel Allocation
  - Location Management
  - Mobile Agents
  - Wireless Overlay Network
  - Adaptive Resource Reservation
  - Route Optimizations

B. Exams

For this course we determined that a 2 to 3 days take home exam is more suitable than an in-class exam. The reason being that a take home exam allows the students to think in some depth various aspects of an answer. Further, the questions can be much broader than are allowed by 1 to 2 hrs. in-class exam. A sample exam is given in Figure 3.

C. Term Projects

In addition to the homework assignments, we also required the students to work on semester long term projects (both experimental and survey type). The objective was that the students should choose a topic of their own like, study it on their own (with help from the instructors) and will learn about in much more depth that they didn't get from the class lectures. Students worked on these projects in groups of at most two students; they were required to provide periodic reports of their progress in addition to their final reports at the end of the semester. Further, each group gave an in class presentation on their term project. Some of the term project topics, that were chosen by the students, are as follows:

- Evaluation of mobile client caching schemes
- Comparative study of routing schemes in mobile ad hoc networks
- Development of scheduling algorithms for mobile agents
- Survey of transaction management schemes in mobile databases

VI. Course Evaluation and Achievements

The first time the course was offered in Fall semester of 1998 and again in Spring semester of 2000. The prerequisite for the course was undergraduate courses in Operating Systems and Computer Networking. The course was taken by eight graduate students the first time and nine graduate students the second time. It was an interesting challenge to cover all the topics in the course outline. A few of the topics required more time than anticipated. We tried to combine some of the topics into one in order to save time. For example, the topics of modeling and simulation of mobile systems was distributed among different topics. Performance implications of a particular scheme, such as data caching and location management, were discussed along with those schemes. This not only helped in making it possible to cover all the topics but also provided performance-centric motivation for some of the topics covered in the class.

As a programming assignment students wrote a CSIM-based simulator for a Mobile-IP adaptive location management scheme. The only additional resource that was required in addition to UNIX workstations in the laboratory was CSIM site license which our department already had. Students were allowed to discuss their design concepts among themselves. However, each student was required to write his/her own simulation program. Students were provided with a simulation skeleton. Further, no strict deadline was set to turn in the simulation. The emphasis was to get the simulation right rather than to turn in something on time. Students were encouraged to discuss the different alternative approaches in the class. Midterm and end-of-semester course evaluation was used to get feedback from the students regarding the course. The following are some positive feedback provided by the students:

- "Breadth of information was stimulating."
- "[The course was] not restricted to a boring textbook."
- "The method of reading papers and discussing them is a good approach. The advantages are i) we learned how to look critically at the information/idea in the paper, ii) we built the practice of reading and learning how to express technical ideas to a group of technical readers."

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                    Final Exam CS580 (Spring 00)
            (Due Tue.  May 9, 2000 by 9am, MAX points = 100)

Note: Be precise, state all your assumptions, and
      cite all the references. No collaboration. Submit an electronic
      copy of your typed answers (.ps or .pdf).

      Only precise and technical answers will be given full credit.


  1) Explain what are the implications of mobility on
      a) Application design
      b) System design (operating system and networking layers)

  2) Explain the differences between the mobile security scheme
     describe in "Secure Short-Cut Routing for Mobile IP" by Trevor
     Blackwell et al. (URL
     http://www.pdos.lcs.mit.edu/~rtm/papers/usenix94-abstract.html)
     and "Security on the Move: Indirect Authentication Using
     Kerberos" by A. Fox and S. Gribble (also available via ACM
     digital library if you did not receive the copy in the class).

  3) What are the fundamental challenges for Pervasive Computing.

  4) Explain the significance of Client-Proxy-Server architecture
     in developing mobile computing systems. What are its advantages
     and disadvantages? Give examples to support your claims.

  5) Analytically compare the performance of AODV multicast operation
     ("Multicast Operation of the Ad-Hoc On-Demand Distance Vector
     Routing Protocol" Proceedings Mobicom'99) and the shared tree
     multicast scheme by Gerla ("Tree multicast strategies in mobile,
     mulithop wireless networks", Mobile Networks and Applications 4
     (1999), 193-207.).  Your analysis should reflect the effect of
     mobility rate on the performance of the two protocols.  Hint: use
     the the analysis in the paper "Providing reliable and fault
     tolerant broadcast delivery in mobile ad-hoc networks" E. Pagani
     and G. Rossi, Mobile Networks and Applications 4 (1999) 175-192
     as an example.  Note that all the three papers were distributed
     in the class and are also available via ACM digital library.
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Fig. 3. A Sample Exam

One student in the class would have preferred a text book in addition to the technical papers covered in the class. Further, some students would have liked more quizzes and more timely feedback on their assignments.

Many of the students who attended this course got motivated in doing their graduate studies in the area of mobile computing. The following are some titles of master's thesis' completed by student who took this course:

1. A strategy for maintaining cache consistency in a mobile wireless environment (by A. Kahol).
2. Modeling of hidden terminal, mobility and their effect on performance of the IEEE 802.11 MAC protocol (by S. Khurana).
3. Routing during periods of disconnection in wireless ad hoc networks (by M. Bahl).
4. An adaptive location management scheme for PCS networks (G. Varsamopulous).

Results from some of these thesis have been published in technical papers [21], [22], [23], [24]. Further, some of the students are continuing for their Ph.Ds in this area.

There were several lessons learned from teaching a class on a hot research area with such diverse topics. The most important one was that in a course with such diverse topics there should be an unifying theme. For this class we found that the unifying theme is the gist provided in Figure 1. It served as a guiding principle in understanding and relating solutions across different topics. In essence systems built for mobile environment should be able to adapt to dynamic changes in computing environment. Secondly, mobile computing is a multidisciplinary topic and stu-

dents with different backgrounds will take this course. Hence, it becomes important to avoid dealing with topics or emphasizing on topics which requires too much specialized knowledge from one particular field. It also means that the instructor should take into account the backgrounds of students registered for a particular offering of the course and adapt the course material accordingly. This implies that the instructor should be ready to add and/or delete some of the intially planned course topics during the semester. Thirdly, in order to cope with diverse background of students, the assignment deadlines should be flexible. The instructor needs to remember that some of the students will have to learn some extra material on their own in order to do the assignment. In our opinion, the emphasis should be on encouraging the students to do the assignment correctly rather than on submitting the assignment by a given deadline.

VII. Conclusions

We have presented our experience in designing and teaching a graduate level course in mobile computing. The course covers the basics of wireless communication, wireless cellular networks (e.g. PCS), protocols and standards (e.g. IS-41, Mobile IP, Wireless ATM), and dynamic (ad hoc, instant infrastructure) networks. Once the students had a grasp of the nature of wireless communication and the current state-of-art in wireless technology, we covered different issues related to mobility such as location tracking and management of mobile hosts, dynamic channel allocation and service handoff, designing and implementing mobile algorithms/applications is the emphasis of the second half of the course. We also covered mobile information systems, energy-efficient and disconnected operations, context-aware computing and mobile agents. This course gave us an opportunity to integrate our research on mobile computing with our teaching and we were also able to inspire some of them to do further work in mobile computing topics.

The importance of mobile computing (or pervasive computing) is bound to increase in near future. Hence, it is important that some of the topics in mobile computing should be taught to undergraduate students. In order to integrate mobile computing in undergraduate curriculum, there are several questions which remain to be addressed:

- What are the fundamental advances in mobile computing which need to be taught at the undergraduate level?
- Which senior level courses should be enhanced to incorporate these fundamental advances?
- What interdisciplinary projects can students do in the current context?
- Where to find relevant course material? How can teachers cooperate in developing and sharing of education material in mobile computing?

We plan to address this issues by designing and offering an undergraduate course in mobile computing.

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