1994

Building Information Systems for Mobile Environments

Evaggelia Pitoura

Bharat Bhargava
Purdue University, bb@cs.purdue.edu

Report Number:

94-034

Pitoura, Evaggelia and Bhargava, Bharat, "Building Information Systems for Mobile Environments" (1994). *Department of Computer Science Technical Reports.* Paper 1134.
https://docs.lib.purdue.edu/cstech/1134

BUILDING INFORMATION SYSTEMS FOR MOBILE ENVIRONMENTS

Evaggelia Pitoura
Bharat Bhargava

CSD TR-94-034
May 1994

Building Information Systems for Mobile Environments

Evaggelia Pitoura and Bharat Bhargava
Department of Computer Science
Purdue University
West Lafayette, IN 47907-1398
{pitoura, bb}@cs.purdue.edu

Report CSD-TR-94-034

Abstract

It is expected that in the near future, tens of millions of users will have access to distributed information systems through wireless connections. The technical characteristics of the wireless medium and the resulting mobility of both data resources and data consumers raise new challenging questions regarding the development of information systems appropriate for mobile environments. In this paper, we report on the development of such a system. First we describe the general architecture of the information system and the main considerations of our design. Then, based on these considerations, we present our system support for maintaining the consistency of replicated data and for providing transaction schemas that account for the frequent but predictable disconnections, the mobility and the vulnerability of the wireless environment.

Keywords: New Applications, Information Systems, Mobile Computing, Transaction Management, Replication, Distributed Database Systems.

1 Introduction

In the recent past, technical advances in the development of portable computers and the rapidly expanding cordless technology have provided the basis for accessing information systems through wireless connections. Today, when users move, unplug their computer from the local area network, transport it, and plug it back to the local area network at their destination. Wireless technology provides users with the ability to retain their network connection even while moving. This new computing paradigm is called *mobile* or *nomadic* computing. Mobile computing can be viewed as adding a new dimension to the broader vision of universal access to information that allows the mobility of data consumers and data resources.

Until recently, infrastructure research pertaining to mobile computing has mostly focused on networking and operating systems [KS92, DFGQM91, IDGQM91, TYT91, AP91, TD91]. Research in networking and communications includes new addressing and routing schemas, support for efficient multicasting and broadcasting, data compression and relocation transparency. Research in operating system addresses security issues, file systems that support disconnected operations and caching techniques. However, the issues introduced go beyond those areas and directly affect information management systems [AK93, IB93b]. Mobile computing introduces new challenging problems concerning resource management, information acquisition [IB92], and data distribution [HSW94].

In this paper we report on the design of an information system for a mobile environment. The goal of this paper is twofold. First, we give a general overview of the organization of the system and of the important concerns of our design. Second, we focus on our system support for consistency and transactions and show how our schema is in compliance with the general architecture and design concerns.

The structure of this paper is as follows. In Section 2, we introduce the physical architecture, and identify the characteristics of the wireless medium and of the mobile hosts. In Section 3 we define the operation modes of a mobile host, present the general object-based architecture of the information system, and introduce the main considerations of the design. The following two sections focus on consistency and transaction management. Section 4 describes our schema for maintaining the consistency of replicated data. The novelty of this schema is the existence of two types of operations (loose and strict) that allow the users to specify the required degree of consistency of their input data. The schema takes into consideration the modes of operation and the peculiarities of the mobile environment. Section 5 discusses the structure of a mobile computation. We argue that flat transactions are inadequate for modeling interactions in a mobile environment and we propose appropriate extensions that account for mobility and recovery. In Section 6, we briefly report on the status of our system. We conclude in Section 7 by summarizing the main results of our work.

2 The Characteristics of the Mobile Environment

Distributed systems that support mobility are physically structured as shown in Figure 1 [IB93b]. The architecture consists of two distinct types of hosts: mobile hosts and fixed hosts. Some of the fixed hosts, called *base stations*, or *mobile support stations*, are augmented with a wireless interface to communicate with mobile hosts. The geographical area covered by a base station is called a *cell*. Each mobile host can directly communicate with one base station, the one covering the geographical area in which the mobile host moves. The process during which a mobile host enters a new cell is called *hand-off*. Usually, cells overlap to accomodate smooth hand-off.

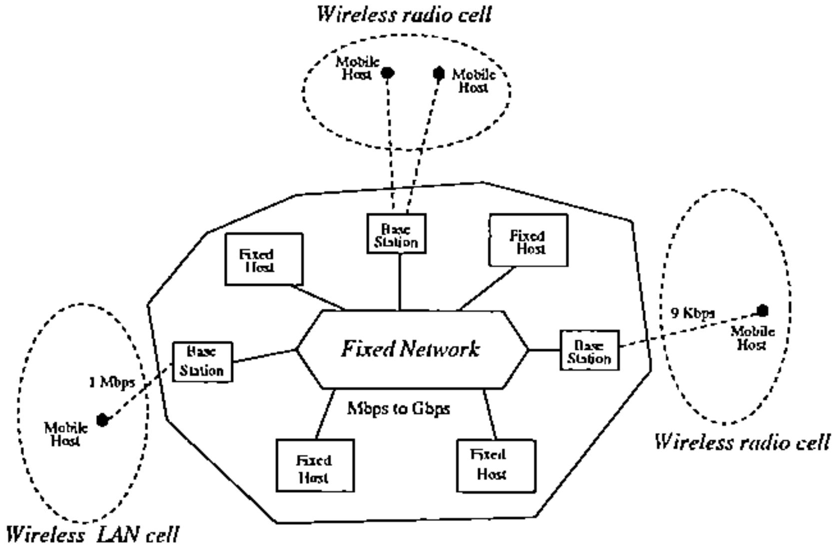

Figure 1: Mobile System Architecture

2.1 The Wireless Medium

The networking infrastructure (also called Personal Communication Network (PCN)) is expected to include [FZ93, IB93b, AK93]:

- *cellular or packet radio* modems (e.g., Ericson GE's Mobidem), which are characterized by high costs, large range coverage, and relatively small bandwidth;
- *satellite services* (e.g., Motorola's Iridium), which provide wide coverage, but are very expensive, usually receive-only and of very low bandwidth; and
- *wireless LANs* (traditional LANs extended with a wireless interface, e.g., NCR WaveLAN, Motorola's ALTAIR, Proxims Range LAN and Telesystem's ARLAN), which provide connectivity within a very small geographical area with low cost.

While the growth in physical network bandwidth has been tremendous (in current technology Ethernet provides 10Mbps, FDDI 100 Mbps and ATM 155 Mbps), products for wireless communication achieve only 2Mbps for radio communication, and 9-14 kbps for cellular telephony [FZ93]. Wireless LANs will provide connectivity within a small geographical area (at a range of a few kilometers) and their typical bandwidth ranges from 250 bps to 2Mbps and it is expected to increase to 10Mbps. Cellular and packet radio modems will cover larger geographical areas. Since the bandwidth is divided between the users sharing a shell, the deliverable bandwidth per user will be lower. Thus, it is safe to assume that bandwidth will continue to be a scarce resource. Bandwidth consumption should be a major concern of mobile computing designs, also because data transmission over the air is *monetarily expensive* [Hay92].

The *frequency* of disconnections is very high in comparison with non-mobile environments. Furthermore, the wireless medium is characterized by much greater variation in network bandwidth than traditional designs, leading to various *degrees of disconnections* depending on the available bandwidth and noise of the communication channel [FZ93, IB93a]. Certain disconnections are considered *foreseeable*, since they can be detected by changes in the signal strength, by predicting the battery's lifetime, or by utilizing knowledge of the bandwidth distribution [AK93, IB93a].

Product	RAM	MHz	CPU	Batteries hours, type	Weight lbs	Display sq. inches
Amstard Pen Pad PDA600	128 KB	20	Z80	40, AAs	0.9	10.4
Apple Newton Message Pad	640KB	20	ARM	6-8, 4 AAAs	0.9	11.2
At&T EO 440	4-12 MB	20	Hobbit	1-6 , NiCad	2.2	25.7

Table 1: Typical values of the mobile hosts

2.2 Mobile Hosts

Mobile hosts, regardless of future technology advances, will have limited computing power, memory and screen size as a result of their small size and weight. Some typical values are shown in Table 1 [FZ93]. Mobile hosts range from small palmtops (e.g., Apple Newton) or specialized data entry devices (like the ones used by UPS) to tabletop computers with wireless interfaces (e.g., AT&T EO). Mobile hosts have limited battery capacity, two or three hours under normal use, which is expected to increase only 20% over the next 10 years. Due to this fact, energy preservation is an important consideration. Moreover, mobile hosts are more susceptible to loss, destruction and theft than static hosts. Table 2 summarizes the characteristics of the wireless medium and of the mobile hosts.

characteristics of the wireless medium	characteristics of mobile hosts
low bandwidth	small size
frequent disconnections	small screen
high bandwidth variability	limited battery life
predictable disconnections	susceptible to theft, and accidents
monetarily expensive	
broadcast is physically supported in a cell	

Table 2: Summary of the Characteristics

3 System Overview

While in a nonmobile distributed system a host operates in one of two modes regarding its connection to the rest of the network (either connected to it or totally disconnected from it) in a mobile environment there are more modes of operation. We model the different modes of operation of a mobile host using the state diagram shown in Figure 2.

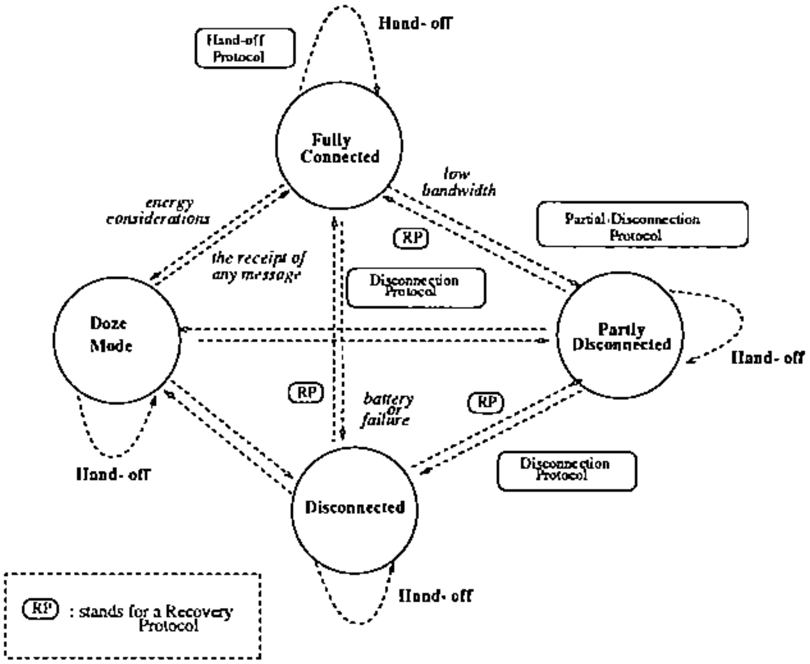

Figure 2: Operation Modes of a Mobile Host

The degree of connection is related to the availability of bandwidth. Since total and partial disconnections are very frequent, they should not be treated as failures. On the contrary, a mobile host should be capable of operating even under low or no connection with the fixed network. A mobile host operates in a *partly disconnected* mode when the communication through the wireless network is limited. In addition to the modes related to the type of connection with the fixed network, a mobile host may switch to the *doze mode* for preserving energy. While in this mode, the clock speed is reduced and no user computation is performed. The mobile host returns to normal operation upon receipt of any message.

Since most of the transitions between modes are predictable, protocols can be designed to prepare the system for the transition.

- A *disconnection protocol* is executed before the mobile host is physically detached from the fixed network. The protocol should ensure that enough information is locally available to the mobile host for its autonomous operation during the disconnection. It should also notify any interested parties for the forecoming disconnection.
- A *partial-disconnection protocol* prepares the mobile host for operation in a mode where all communication with the fixed network should be as restricted as possible. Selective caching can be used for caching data, whose presence in the host will minimize future network use.
- *Recovery protocols* re-establish the connection with the fixed network and resume normal operation.
- *Hand-off protocols* refer to passing the boundaries of a cell. State information pertaining to the mobile host should be transferred to the base station of the new cell.

Part of these protocols is handled by low-level system operations. However, the modes are not necessarily completely transparent to the applications. Support by the application and in our case by the database system can lead to performance gains. For example, information about the type of application can be used to design caching techniques or to limit network access.

In this paper, we focus on how system support for transactions and consistency maintenance can take into account the modes of operation to increase performance and availability. Specifically, in Section 4 we present a replication controller, which adjusts with the type of connection. In Section 5 we introduce the concept of transaction migration to handle hand-offs.

In the remainder of this section, we describe the general architecture of the system and we conclude with two important considerations in the design of an information system for a mobile environment.

3.1 The Architecture of the Information System

A user of a mobile host will have access to a variety of information resources, which will be located in both mobile and static hosts. These information resources can be characterized as *mobile* for two different reasons. On the one hand, because they may be produced and stored in mobile hosts and on the other hand, because they may be dynamically relocated to better suit the fast changing distribution of data consumers and data producers.

The use of mobile hosts increases the scale and thus the *heterogeneity* of the information systems involved in the distributed computation. Furthermore, mobility adds to the heterogeneity since users of mobile hosts are entering new cells and possibly heterogeneous environment. As a consequence, heterogeneity becomes a decisive factor in the design of information systems for mobile environments. Many of the information systems that participate in a distributed system correspond to *pre-existing* applications that were built without taking into account the possibility of their future access through wireless connections. Rather than rebuilding them, building appropriate interfaces on top of them is a more realistic approach.

Because of the above considerations, an *object-based architecture* seems to be appropriate to serve as the architecture of a mobile information system. In object-based architectures, *objects* model information resources and *methods* model information services [NWM93]. These architectures are appropriate since:

- They hide the heterogeneity of the environment, since the response to a message depends only on the interface and not on the internal implementation of the object or the method.

- Special object servers can be built that will offer appropriate methods for accessing data. These methods will account for the wireless of the medium and the fact that the location of a client is a frequently changing data, see Figure 3.

The distributed object-based architecture provides the high-level architecture of the distributed heterogeneous information system. Internally, each information system that participates in the object-based architecture may support its own data model. What would be an appropriate internal data model for a local mobile database is not clear yet, but it should support graphical interfaces and take into account the inherent heterogeneity of the mobile environment [AHK93].

Location Databases In addition to the servers that will provide wireless access to general information resources, the system should maintain servers

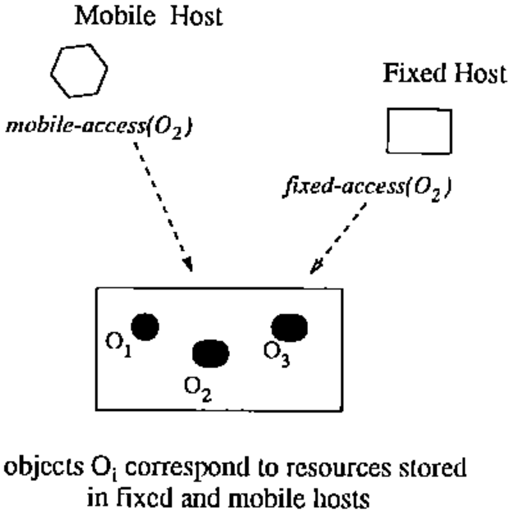

Figure 3: Object-based Architecture

that offer access to information systems that contain location-related information. We assume at least two such databases, one per user that would include the user's home address and other user-related information and one per base station that would include information about all hosts under its cell. Location databases are:

- fast changing,
- geographical,
- distributed and replicated over many sites to support efficient access,
- imprecise, since the overhead for keeping them up-to-date may be overwhelming.

Data stored in location databases may participate in queries. This results in queries that are:

- of different complexity in terms of location constraints,
- geographical and moreover dependent on the location of the user (e.g. find the nearest restaurant),

- real-time,
- imprecise,
- dependent on the user's direction of move

Query issues involving location data are discussed in [IB92]. In Section 4, we discuss issues regarding the consistency of such data.

3.2 Two Important Considerations

Two issues of particular interest in designing information systems for mobile environments are to determine the role of a mobile host in a distributed computation and to *personalize* the computation. We discuss them further.

The Role of a Mobile Host There is no agreement yet on the role of a mobile host in a distributed environment. The possibilities range from that of a dumb terminal with no autonomy to that of a relatively independent component with enough memory and computing power to perform part of the distributed computation locally. Each approach has both advantages and disadvantages. Performing part of the computation on a mobile host:

- costs in terms of power consumption,
- complicates data replication and integrity preservation,
- adds to the search cost of locating mobile hosts and the data that they produce and consume.

On the other hand, it

- allows the autonomous operation of the mobile host during partial and total disconnections,
- may limit bandwidth use,
- may save the energy cost for the transmission of data to and from the fixed network.

In our design, we adopt the approach that part of the computation will be executed in a mobile host because we believe that allowing a mobile host to operate autonomously is very important especially since disconnections are very frequent. But still, since mobile hosts are susceptible to failures and accidents, part of the computation must be reported to the fixed network. In Section 5, we introduce the notion of transaction proxies that provides transaction support for backing-up the computation in the fixed network.

User's Profile Utilizing information about users gains increasing importance as information systems scale in size. We assume that this information is stored in the *user's profile*. Information about users is very important to data navigation since it can be used to select the information that is of interest to a particular user. For instance, users may be informed for the release of the latest album of their favored artist. Specifically in mobile environments, the user's profile include also information about the user's *mobility pattern*, for instance the fact that each day he commutes to his office. The user's profile can be part of the location database of the user.

In mobile systems research the user's profile has been widely used, for example to determine which data to cache before disconnections [KS92], or to optimize queries about location [IB92]. In our schema, we propose using information about users to define consistency clusters (Section 4) and to simulate mobility (Section 6).

4 Consistency of Replicated Data

Communication through the wireless network is very expensive both monetarily and in terms of bandwidth consumption. As a consequence, performing operations locally in a mobile host can lead to performance gains and increase availability during total and partial disconnections. On the other hand, maintaining full consistency among data saved in fixed and mobile hosts imposes unbearable overheads in mobile environments [AK93, IB93a, PB93]. We propose a more flexible model. The formal definition of the model, its scope and the associated correctness criteria are presented in [PB94]. The presentation of the model in this section aims at demonstrating how the operation modes, and the other general considerations are taken into account in designing the replication controller of our information system.

We group together in a cluster all data that are semantically related or closely located. While full consistency is required for all copies of a data item inside a cluster, degrees of consistency are defined for replicas located at different clusters. The degree may depend on the availability of bandwidth in that while in a partly-disconnected mode, applications may have to tolerate high degrees of inconsistency. We allow transactions to exhibit certain degrees of tolerance for inconsistencies by introducing strict and loose operations. Loose operations are operations that can be executed under relaxed consistency requirements.

4.1 Clustering

We partition the items of a mobile database into *clusters*. All replicas in a cluster are synchronized, while replicas at different clusters may vary by some appropriately defined degree. In that sense, a cluster is the unit of consistency. The degree of inconsistency may vary based on the availability of network bandwidth by allowing small deviation among the copies in cases of higher bandwidth availability and higher deviation in cases of low bandwidth availability. The cluster configuration is *dynamic* rather than static. When clusters are merged the values of all copies of a data item are reconciled.

Defining Degrees There are many alternative ways of defining degrees [SR90]. The *degree* may express the divergence from the value of the primary copy [ABGM90]. In this case, the allowable degree may be bounded by limiting the number of versions, by setting a maximum value on the allowable deviation, or by limiting the number of transactions that can operate on inconsistent values. Alternatively, we can define the degree as the number of data items or the number of data copies per data item that can diverge.

Defining Clusters One possible way of defining a cluster is by grouping together data residing in the same or neighboring hosts. For instance, data stored in hosts that are partially or totally disconnected from the fixed network may be considered as forming a cluster (Figure 4). In this case, by taking advantage of the predictable nature of disconnections, clusters of data may be explicitly created or merged upon a forecoming disconnection or connection of the associated mobile host.

Furthermore, clusters may be defined based on the type of data. A characteristic example of such data is the data representing the *location* of mobile hosts. Since this type of data are fast-changing, the maintenance of their full consistency could cause unbearable overheads. The definition of clusters may be also explicitly provided by the users based on the semantics of their data or applications. Information stored in a *user's profile* may also be utilized to determine clusters. For example, data that are most frequently accessed by a user or data that are in a great extent private to a user can be considered as belonging to the same cluster independent of their location.

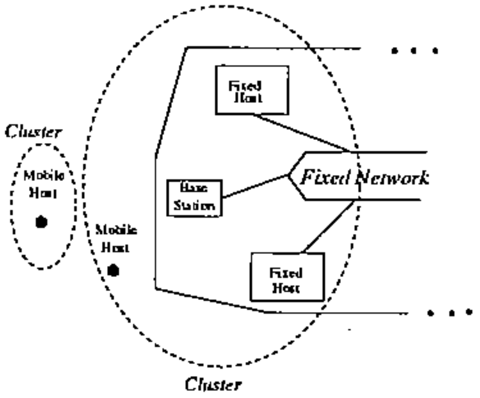

Figure 4: A possible cluster configuration, where clustering is based on location

4.2 Handling Loose Consistency

To maximize local processing and limit network accesses, we propose allowing the user to interact with locally (in a cluster) available data by introducing two new kinds of operations, loose reads and loose writes. These operations allow users to operate on loosely consistent data when the lack of strict consistency does not affect the semantics of their transactions. Allowing users to operate on local data is especially important during total or partial disconnection since those data are then the only data that are accessible or affordable to access. We call the standard read and write operations strict read and strict write operations to differentiate them from the loose operations.

Specifically, a loose read ($LR[a]$) reads the value written by the last loose or strict write operation on a *locally* available copy, that is on a copy in its cluster. A *loose write* operation ($LW[a]$) writes some local copies and is not permanent unless it is finally committed after cluster merging. A *strict read* operation ($SR[a]$) reads the value written by the last strict write operation on a copy located in *any* of the clusters. Finally, the value written by a *strict write* operation ($SW[a]$) becomes permanent after commitment. Our method can be implemented as a 2-version method. Local transaction managers may maintain two copies of a data item, one that is updated by strict writes and one that is updated by both strict and loose writes. The first is read by strict read operations and the second by loose read operations.

Two Types of Basic Transactions We distinguish two types of transactions:

(a) transactions that consist only of loose read and loose write operations and are called *loose transactions*; and

(b) transactions that consist only of strict read and strict write operations and are called *strict transactions*.

Loose transactions are locally committed in their associated clusters. Updates performed by locally committed transactions are revealed only to other loose transactions in the same cluster. These changes are revealed to strict transactions only after merging, when local transactions become globally committed. Before global commitment a loose transaction may be undone even after it has been locally committed.

	$LR_j(a_k)$	$SR_j(a_k)$	$LW_j(a_k)$	$SW_j(a_k)$
$LR_i(a_k)$			X	X
$SR_i(a_k)$				X
$LW_i(a_k)$	X		X	X
$SW_i(a_k)$	X	X	X	X

Table 3: Conflict relation, a "x" entry indicates that the operations for the given row and column conflict. Row entries correspond to operations of transaction T_i and column entries to operations of a transaction T_j, where $i \neq j$

A loose transaction is a transaction that may read loosely consistent data and whose writes may be undone any time before merging. Strict transactions have the usual semantics. Loose transactions may be useful for many applications that do not require exact values of data such as gathering information for statistical purposes. Allowing updates in loose transactions adds functionality. These updates are finally committed only if they do not conflict with the operations of a strict transaction. Thus loose updates are especially useful for handling private data or seldomly accessed data, for which conflicts are rare.

Users or application developers are able to specify the loose or strict requirements of their transactions through a high-level interface. Then, the operations of each transaction are automatically translated into loose or strict operations according to the given specifications.

Correctness Two operations of the same transaction conflict if they both access the same data copy and at least one of them is a write. Operations of two different transactions that are executed before cluster merging conflict as shown in Table 3. Upon merging of clusters we adopt a strictly syntactic approach to establishing full consistency. We undo all loose transactions whose loose writes conflict with a strict transaction. Serializability-based criteria for the correctness of schedules before and after merging are formally defined in [PB94]. In [PB94], we have also presented graph-based tests for the serializability of the corresponding schedules.

5 Transactions in a Mobile Environment

Loose and strict transactions are generic transactions that can be considered *part* of a general mobile transaction that models the interaction of a user with a mobile distributed system. Generally speaking, a *mobile transaction* is a distributed transaction T, where some parts of the computation are executed on mobile and some parts on nonmobile hosts. The model for such a transaction that involves data stored in both the fixed and the wireless network has not emerged yet.

A large number of transactions in a mobile environment is expected to be read-only transactions, where users will query large amount of data. Still some applications such as inventory control, banking applications and travel reservations will require updates. For instance, a traveling salesman will update an inventory database to reflect the fact that an item has been sold. Consumers will use their mobile host to book flights, buy tickets or do banking transactions.

An important issue is what part and how large a part of a transaction will be executed on a mobile host. This is related to the role of a mobile host in a mobile distributed environment. Operations on a mobile host may minimize network access, and optimize response time. On the other hand, they cost in terms of local resource consumption (especially battery energy). But the decisive factor for answering this question is frequent disconnections. To allow the operation of a mobile host during disconnections some part of the computation must be executed locally.

Characteristic of Mobile Transactions We identify the following as the characteristics of a mobile transaction,

- Mobile transactions are transactions that involve the wireless network and may be executed in both mobile and nonmobile hosts.
- Using the *wireless medium* has the following consequences. Transactions tend to be:
  1. monetarily expensive;
  2. long lived, because of long network delays;
  3. error-prone, because of frequent disconnections but also because mobile hosts are more prone to accidents than fixed hosts; and
  4. session-based. For some technologies, such as cellular modems, there is a high start-up charge for each communication. Cost-effective transaction management may adopt the approach of supporting few long-lived session-based transactions instead of many short-lived transactions.
- *Mobility* results in transactions with the following characteristics:
  1. Transactions access heterogeneous information systems.
  2. Transactions access (possibly imprecise) location data.
  3. Transactions may involve data that are dynamically relocated.

Modeling Mobile Transactions Mobile transactions are long-running, error-prone and heterogeneous. As a consequence, modeling mobile transactions as ACID transactions is very restrictive. The expressive power of ACID transactions is very limited, they offer no way of modeling computations with a complex control structure. Furthermore, ACID transactions do not support partial commitment or abortion of a part of a transaction, or partial recovery. There is no way of "suspending" a transaction to survive a disconnection.

It seems that an *open-nested model* [GR93] is more appropriate for modeling mobile transactions. In that model, a transaction consists of a number of subtransactions with a specified set of dependencies. The set of dependencies varies based on the application and it can be customized. In [Chr93] an axiomatic definition of a transaction model for mobile transactions is presented. Our approach is different in that, instead of defining a powerful, general transaction model, we attempt to identify the *generic characteristics* that this model must support to be appropriate for a mobile environment.

More specifically, to deal with the particularities of the wireless medium, we have introduced *loose transactions.* Loose transactions support disconnected operations, and minimize bandwidth use. Moreover, they are capable of modeling operations on imprecise data, such as location data. In this section we investigate further on the structure of mobile transactions. We present two generic techniques:

- To deal with the mobility of the environment we introduce the concept of *transaction migration.*
- To deal with the vulnerability of the mobile hosts we introduce the concept of a *transaction proxy.*

5.1 Transaction Migration

A mobile host may enter a new cell while in operation. In that case, it may be necessary to *migrate* part of the computation that was executed in a fixed host to another fixed host. One motivation for migration is improvement in performance. By moving the computation close to the mobile host, the communication cost is minimized. Transaction migration (relocation) can be thought of as the dual of data relocation. Furthermore, a base station may not be willing to support computation initiated by users that are not any more in its cell. The reason for this policy may be security considerations or load balancing techniques among the base stations. In that case, transactions submitted to the old base station must be transferred to the new base station.

Let T_i be a transaction that was initially executed at site i and then was migrated to site j. We use the notation $T_{i \rightarrow i}$ for the part executed at site i and $T_{i \rightarrow j}$ for the part executed at site j. $T_{i \rightarrow i}$ cannot be committed in site i but it may conditionally release some of the local resources it holds. $T_{i \to j}$ inherits state information from $T_{i \to i}$. That information depends on the consistency control method used. It may include timestamps, requested and granted locks, or log files.

5.2 Transaction Proxies

To deal with the fact that mobile hosts are more susceptible to theft accidents and frequent disconnections, we must report part of the computation that is performed in a mobile host to the fixed network. We model that by the concept of "transaction proxies". For each transaction T_i executed at a mobile host i, we define a dual transaction PT_j, called proxy, that will be executed on host j, where j is the base station of i.

A proxy transaction may be considered as a subtransaction of the original transaction. Thus, any time a subtransaction is submitted to a mobile host its proxy transaction is submitted to its base station. The proxy transaction includes only the updates of the original transaction. Alternatively, proxy transactions may be executed off-line. In that sense, proxy transactions corresponds to taking periodic back-ups of the computation which is performed on a mobile host.

6 Status Report

We are currently developing an information system on top of ORAID [BJS93]. ORAID is an object-oriented system built on top of RAID [BR89], a distributed database system that has been proven successful in supporting experiments in communication, adaptability, and transaction processing. We are modifying the communication library routines [ZB93] to simulate the wireless communication. Mobility is captured by connecting our simulated mobile station with different base stations. The mobility patterns are given as part of the user profile. We assign to each host that simulates a mobile host, a fixed host which serves as its base station. The mobile host can then directly communicate only with its assigned base station. The assignment of base stations to mobile hosts is dynamic and is driven by the mobility pattern as specified in each user's profile.

We intend to provide system support for loose transactions, migration and proxies and study the performance of these mechanisms. In addition to the traditional performance measurements the mobile environment introduces new performance concerns, that include

- energy preservation (battery is a limited resource);
- prudent use of the bandwidth (bandwidth in mobile environment is a very scarce and expensive resource); and
- the degree of autonomy during weak or total disconnections (since disconnections are frequent, mobile computers should be able to operate even while disconnected).

7 Summary

Wireless communications offer the exciting possibility of accessing information independent of location and movement. This possibility raises new challenges to the design of information systems. In this paper we have reported on the design of such a system. The contribution of this paper is twofold. First we have:

- defined the operation modes of a mobile host;
- proposed a general object-based architecture for information systems appropriate for mobile environments; and
- identified the main concerns in designing mobile information systems.

Second, we have shown how these general principles can be used to provide system support for transactions in a mobile environment. Specifically, we have introduced:

- loose transactions to deal with the frequent, predictable and of various degrees disconnections,
- transaction migration to model mobility, and
- transaction proxies to handle recovery.

Finally, we have briefly reported on the status of our system and establish performance criteria for testing the proposed techniques.

References

[ABGM90] Rafael Alonso, Daniel Barbara, and Hector Garcia-Molina. Data Caching Issues in an Information Retrieval System. *ACM Transactions on Database Systems*, 15(3):359–384, September 1990.

[AHK93] Rafael Alonso, Eben M. Haber, and Henry F. Korth. A Mobile Computer Interface for Heterogeneous Databases. In *Proceedings of the RIDE-IMS'93 Workshop*, Vienna, Austria, April 1993.

[AK93] Rafael Alonso and Henry F. Korth. Database System Issues in Nomadic Computing. In *Proceedings of the 1993 SIGMOD Conference*, Washington, D.C., May 1993.

[AP91] Baruch Awerbuch and David Peleg. Concurrent Online Tracking of Mobile Users. In *Proceedings of the ACM SIGCOMM Symposium on Communications, Architectures and Protocols*, pages 221–233, September 1991.

[BJS93] Bharat Bhargava, Yinhe Jiang, and Jagannathan Srinivasan. O-Raid: Experiences and experiments. In *International Conference on Intelligent and Cooperative Information Systems, Rotterdam, Holland*, May 1993.

[BR89] Bharat Bhargava and John Riedl. The Raid distributed database system. *IEEE Transaction on Software Engineering*, 15(6), June 1989.

[Chr93] Panos K. Chrysanthis. Transaction Processing in Mobile Computing Environment. In *Proceedings of the IEEE Workshop on Advances in Parallel and Distributed Systems*, pages 77–83, Princeton, New Jersey, October 1993.

[DFGQM91] Daniel Duchamp, Steven K. Feiner, and Jr Gerald Q. Maguire. Software Technology for Wireless Mobile Computing. *IEEE Network Magazine*, pages 12–18, November 1991.

[FZ93] George H. Forman and John Zahorjan. The Challenges of Mobile Computing. Technical Report UW-CSE-TR #93-11-03, University of Washington, Dept. of Comp. Science& Engineering, December 1993.

[GR93] Jim Gray and Andreas Reuter. *Transaction Processing: Concepts and Techniques*. Morgan Kaufmann, 1993.

[Hay92] D. Hayden. The New Age of Wireless. *Mobile Office*, May 1992.

[HSW94] Yixiu Huang, Prasad Sistla, and Ouri Wolfson. Data Replication for Mobile Computers. to appear in SIGMOD 94, 1994.

[IB92] T. Imielinski and B. R. Badrinath. Querying in Highly Mobile Distributed Environments. In *Proceedings of 18th VLDB*, pages 41–52, August 1992.

[IB93a] Tomasz Imielinksi and B. R. Badrinath. Data Management for Mobile Computing. *SIGMOD Record*, 22(1):34–39, March 1993.

[IB93b] Tomasz Imielinksi and B. R. Badrinath. Wireless Mobile Computing: Challenges in Data Management. Technical Report DCS-TR-296 and WINLAB TR-49, Rutgers, Dept. of Comp. Sciences, 1993. to appear in Communications of the ACM, 1994.

[IDGQM91] John Ioannidis, Dan Duchamp, and Jr Gerald Q. Maguire. IP-based Protocols for Mobile Internetworking. In *Proceedings of the ACM SIGCOMM Symposium on Communications, Architectures and Protocols*, pages 235–245, September 1991.

[KS92] James J. Kistler and M. Satyanarayanan. Disconnected Operation in the Coda File System. *ACM Transactions on Computer Systems*, 10(1):3–25, February 1992.

[NWM93] John R. Nicol, C. Thomas Wilkes, and Frank A. Manola. Object Orientation in Heterogeneous Distributed Computing Systems. *IEEE Computer*, 26(6):57–67, June 1993.

[PB93] Evaggelia Pitoura and Bharat Bhargava. Dealing with Mobility: Issues and Research Challenges. Technical Report TR-93-070, Purdue University, Dept. of Comp. Sciences, 1993.

[PB94] Evaggelia Pitoura and Bharat Bhargava. Maintaining Consistency of Data in Mobile Distributed Environments. Technical Report TR-94-025, Purdue University, Dept. of Comp. Sciences, 1994.

[SR90] Amit Sheth and Marek Rusinkiewicz. Management of Interdependent Data: Specifying Dependency and Consistency Requirements. In *Proceedings of the Workshop on the Management of Replicated Data*, pages 133–136, Houston, Texas, November 1990.

[TD91] Carl D. Tait and Dan Duchamp. Service Interface and Replica Management Algorithm for Mobile File System Clients. In *Proceedings of the First International Conference on Parallel and Distributed Information Systems*, pages 190–197, 1991.

[TYT91] Fumio Teraoka, Yasuhiko Yokote, and Mario Tokoro. A Network Archtecture Providing Host Migration Transparency. In *Proceedings of the ACM SIGCOMM Symposium on Communications, Architectures and Protocols*, pages 209–220, September 1991.

[ZB93] Yongguang Zhang and Bharat Bhargava. Wance: A Wide Area Network Communication Emulation System. In *Proceedings of IEEE Workshop on Advances in Parallel and Distributed Systems*, pages 40–45, Princeton, NJ, October 1993.