Nomadic Computing*

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1 INTRODUCTION

Since the beginnings of telecommunication technology, we have witnessed a number of major shifts in the application of communications to the needs of our society and industry. In that process, we have seen the marriage of wireline and wireless technologies, of analog and digital technologies, of voice, data, video, image, fax, graphics, etc., to create a computer-communications infrastructure that spans the globe and serves billions of people.

We are now in the midst of an accelerating groundswell in this field of computer-communications in its largest sense (i.e., not simply the wires and networks, but also the infrastructure, the middleware, the applications, the uses and users of the technology) (CSTB, 1994) Witness the fact that the Internet is now a household word. The use of the Worldwide Web (WWW) is growing faster than any other application we have ever witnessed in 27 years of networking (from the day the ARPANET was born at UCLA in September 1969 up to the present); and the WWW is still in its infancy!

Most people function in a world where their desktop computing appliance is connected through a corporate or private network to a server located "someplace else" (possibly in a dungeon in some mysterious basement). It is usually assumed that the connectivity provided by this network is reliable and of high bandwidth (typically megabits per second). But, in fact, most of us are nomads, moving between office, home, airplane, hotel, automobile, branch office, conference room, bedroom, etc. In so doing, we often find ourselves decoupled from our "home base" computing and communications environment. As we move around, we find enormous variations in the computing platform to which we have access (advanced workstation, pentium-class PC, laptop, palmtop), in the quality of the printers and displays that are available, in the communication device we use (Ethernet attachment, PCMCIA card, analog modem card, CDPD wireless data channel) as well as in the communication bandwidth that is available to us (wireless at 9.6 Kbps, modem at 28.8 Kbps, ISDN at 112 Kbps, Ethernet at 10 Mbps, ATM at 25 or 155 Mbps). And, in addition, we may choose to do computing and/or communicating while we are on the move.

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The variety of portable *computers* is impressive, ranging from laptop computers, to notebook computers, to personal digital assistants, to smart credit card devices, to wrist watch computers, etc. In addition, the *communication* capability of these portable computers is advancing at a dramatic pace from high speed modems, to PCMCIA modems, to email receivers on a card, to spread-spectrum hand-held radios, to CDPD transceivers, to portable GPS receivers, to gigabit satellite access, etc.

The combination of portable computing with portable communications is changing the way we think about information processing . We now recognize that access to computing and communications is necessary not only from one's "home base", but also while one is in transit and when one reaches one's destination[1].

Even without portable computers or communications, there are many who travel to numerous locations in their business and personal lives, and who require access to computers and communications that are available at their destination when they arrive there. Indeed, a move from one's desk to a conference table in one's office constitutes a nomadic move since the computing platforms and communications capability may be considerably different at the two locations.

A fundamental way in which nomadic computing differs from conventional operation is the huge variability in connectivity to the rest of one's computing environment. That level of connectivity often includes extended periods of low bandwidth or no communication at all. Since many users and programs make intermittent, but nevertheless essential, use of "off-machine" information and services, they will be unable to operate effectively unless extraordinary steps are taken. The goal of "transparent virtual networking" is precisely to permit users and programs to be as effective as possible in this environment of uncertain connectivity without changes to the manner in which they operate. That is, transparent virtual networking makes the sometimes connected computer operate in the same way and as effectively in standalone operation as when it is connected to the organization's information network.

These ideas form the essence of a major shift to *nomadicity* (nomadic computing and communications) that we choose to address in this paper. *Nomadicity may be defined as the system support needed to provide a rich set of computing and communication capabilities and services to nomads as they move from place to place in a transparent, integrated and convenient form*.

In this paper we discuss our vision of the nomadic computing environment from a systems perspective, with specific attention to the software system issues that must be addressed in the design of a transparent virtual networking interface to support the nomadic user.

2 NOMADIC COMPUTING[2]

We are interested in those capabilities that must be put in place to support nomadicity. The desirable characteristics for nomadicity include independence of:

- location;
- motion;
- computing platform;

[1] Moreover, one may have more than a single " home base"; in fact, there may be no well-defined " home base" at all.

[2] Some of the ideas presented in this section were developed with the Nomadic Working Team (NWT) of the Cross Industrial Working Team (XIWT); the author is the chairman of the NWT (NWT, 1995) In addition, portions of this section were described in (Kleinrock, 1995)

- communication device;
- communication bandwidth.

and with widespread presence of access to remote files, systems and services. The notion of independence here does not refer to the quality of service one sees, but rather to the perception of a computing environment that *automatically adjusts* to the processing, communications and access available at the moment. For example, the bandwidth for moving data between a user and a remote server could easily vary from a few bits per second (in a noisy wireless environment) to hundreds of megabits per second (in a hard-wired ATM environment); or the computing platform available to the user could vary from a low-powered Personal Digital Assistant while in travel to a powerful supercomputer in a science laboratory. Indeed, today's systems treat radically changing connectivity or bandwidth/latency values as *exceptions* or *failures*; in the nomadic environment, these must be treated as the *usual* case. Moreover, the ability to accept partial or incomplete results is an option that must be made available due to the uncertainties of the informatics infrastructure.

Nomadicity exacerbates a number of problems that the user faces. These include the following:

- Disconnectedness
- Variable connectivity due either to voluntary changes (one travels, for example) or unpredictable changes (a noisy wireless connection)
- Variable routes through a network (i.e., changing virtual circuits)
- Variable requirements (in different environments, the needed support level may vary dramatically)
- Resource replication (one may choose to copy files in multiple locations and devices)
- The need for the user to become aware of the changing environment
- The need for the environment to become aware of the presence and location of nomads.
- The need for adaptivity at many levels, including, for example, variable compression requirements to match bandwidth and platform capabilities
- In general, the need to manage distributed "stuff"

Many people think of wireless communications as the enabler, or even the characterization, of nomadicity. The view we take is far broader than that. It is true that wireless communications may be a component of nomadicity, but it is not a necessary component. When people travel across the country and check into a hotel, they have made a nomadic move as they attempt to connect their laptop via a wireline analog modem to the network infrastructure; no wireless communication is there involved. Indeed, we emphasize that much of the action for nomadic computing takes place at the middleware level of the commonly accepted layered architecture. One version of that layered architecture, as put forward in (CSTB, 1994) is shown in Figure 2.1 below. In this figure we clearly see the middleware level between the applications level and the transport level. Most of the functionality we describe will be found at this level. However, some of the interfaces to the network technology substrate refer to functionality at the Open Data Network (ODN) Bearer Service level.

Figure 2.1 The Open Data Network Architecture

2.1 System Parameters

Some of the key system parameters with which one must be concerned include: bandwidth; latency; reliability; error rate; delay; storage; processing power; interference; interoperability; user interface; cost; etc. These are the usual concerns for any computer-communication environment, but what makes them of special interest for us is that the values of these parameters change *dramatically* (and sometimes suddenly) as the nomad moves from location to location. In addition, some totally new and primary concerns arise for the nomad such as weight, size, battery life, loss, theft, and damage, of his/her portable devices.

2.2 Why is Nomadic Computing of Interest

There are a number of enchanting reasons why nomadicity is of interest. These include:

- Nomadicity is clearly a *newly emerging technology* with which users are already surrounded.
- We judge it to be a *paradigm shift* in the way computing will be done in the future.
- Information technology trends are *moving in this direction*.
- Nomadic computing and communications is a *multi-disciplinary* and *multi-institutional* effort.
- It has a huge *potential for improved capability* and convenience for the user.
- At the same time, it presents at least as huge a problem in *interoperability* at many levels; nomadicity makes all the usual problems much harder.
- The contributions from any investigation of nomadicity will be mainly at the *middleware* level.
- The products that are beginning to roll out have a *short term focus*; however, there is an enormous level of interest among vendors (from the computer manufacturers, the networking manufacturers, the carriers, etc.) for long range development and product planning, much of which is *now underway*.
- Whatever work is accomplished now will certainly be of *immediate practical use*.

3 SYSTEMS RESEARCH ISSUES

There are fundamental new research problems that arise in the development of a nomadic architecture and system. Let us consider a sampling of such problems.

3.1 Nomadic System Architecture

One key problem is to develop a full *System Architecture and Set of Protocols* for nomadicity. These should provide for a transparent view of the user's dynamically changing computing and communications environment. The protocols must satisfy the following kinds of requirements:

- Enable interoperation among many kinds of infrastructures (e.g., wireline and wireless);
- Deal with unpredictability of: user behavior, network capability, computing platform
- Provide for graceful degradation;
- Scale with respect to: heterogeneity, address space, quality of service (QoS), bandwidth, geographical dimensions, number of users, etc.;
- Provide the user with an indication of the QoS he or she is currently receiving, the size of files about to be downloaded, etc.;
- Provide for integrated access to services;
- Allow for ad-hoc access to services;
- Deliver maximum independence between the network and the applications from both the user's viewpoint as well as from the development viewpoint;
- Relieve the user from reconfiguring or rebooting each time the mode of communication access changes;
- Match the nature of what is transmitted to the bandwidth availability (i.e., compression, approximation, partial information, etc.);
- Enable cooperation among system elements such as sensors, actuators, devices, network, operating system, file system, middleware, services, applications, etc.

Some of the system developments that can help in providing these requirements are:

- An integrated software framework which presents a common virtual network layer;
- Appropriate replication services at various levels;
- File synchronization;
- Predictive caching;
- Consistency services;
- Adaptive database management;
- Location services (to keep track of people and devices);
- Discovery of resources.

3.2 Nomadic Reference Model

A second research problem is to develop a *Reference Model for Nomadicity* which will allow a discussion of its attributes, features and structure in a consistent fashion. This should be done in a way that characterizes the view of the system as seen by the user, and the view of the user as seen by the system. The dimensions of this reference model might include:

- System state consistency (i.e., is the system consistent at the level of email, files, database, applications, etc.);

- Functionality (this could include the bandwidth of communications, the nature of the communication infrastructure, the quality of service provided, etc.);
- Locality, or Awareness (i.e., how aware is the user of the local environment and its resources, and how aware is the environment of the users and their profiles).

3.3 Modeling of the Nomadic Environment

A third research problem is to develop *Mathematical Models* of the nomadic environment. These models will allow one to study the performance of the system under various workloads and system configurations as well as to develop design procedures.

The researcher has a number of options at his disposal to use in conducting the performance evaluation task that remains once a mathematical model has been developed. These include:

- Mathematical analysis
- Numerical evaluation
- Iterative solution
- Simulation
- Emulation
- Build the system and measure it

Each of these approaches has its own pitfalls. In the table below, we identify some of these pitfalls:

Option	Problems with the Option
Mathematical Analysis	Non-stationarity, coupled queues, etc.
Numerical Evaluation	Exponential numerical complexity
Iterative Solution	Rate of convergence
Simulation	Difficult to search large solution space
Emulation	Expensive and cumbersome
Build the System & Measure It	Bankrupts you

One way to overcome these many problems is to employ a Hybrid solution whereby many options are incorporated simultaneously. For example, part of the model might be mathematically based, while part may be based on simulation and yet other parts might be portions of the actual system itself. By judiciously selecting which parts are modeled with which options, the analytical task often becomes manageable.

3.4 The Multidisciplinary Nature of Nomadicity

As mentioned above, the area of nomadic computing and communications is multidisciplinary. A list of the disciplines which contribute to this area are (in top-down order):

- Advanced applications, such as multimedia or visualization;
- Database systems;
- File systems;

- Operating systems;
- Network systems;
- Wireless communications;
- Low power, low cost radio technology;
- Micro-electro-mechanical systems (MEMS) sensor technology;
- MEMS actuator technology;
- Nanotechnology.

The reason that the last three items in this list are included is that we intend that the nomadic environment include the concept of an *intelligent room*. Such a room has imbedded in its walls, furniture, floor, etc., all manner of sensors (to detect who and what is in the room), actuators, communicators, logic, cameras, etc. Indeed, one would hope to be able to speak to the room and say, for example, " I need some books on the subject of spread spectrum radios," and perhaps three books would reply. The replies would also offer to present the table of contents of each book, as well, perhaps, as the full text and graphics. Moreover, the books would identify where they are in the room, and, if such were the case, might add that one of the books is three doors down the hall in a colleague's office!

3.5 Other Issues

There are numerous other systems issues of interest that we have not addressed here. One of the primary issues is that of security, which involves privacy as well as authentication. Such matters are especially difficult in a nomadic environment since the nomad often finds that his computing and communication devices are outside the careful security walls of his home organization. This basic lack of physical security exacerbates the problem of nomadicity.

4 WIRELESS ISSUES IN NOMADICITY

It is clear that a great many issues regarding nomadicity arise whether or not one has access to wireless communications. However, with such access, a number of interesting considerations arise which we discuss in this section at a fairly high level; they are discussed in further detail in a number of recent publications (Alwan, et. al, 1996; Jain, et. al 1995; Katz, 1994; Short, et. al. 1995).

Access to wireless communications provides two capabilities to the nomad. First, it allows him to communicate from various (fixed) locations without being connected directly into the wireline network. Second, it allows him to communicate while traveling. Although the bandwidth offered by wireless communication media varies over an enormous range as does the wireline network bandwidth, the nature of the error rate, fading behavior, interference level, mobility issues etc., for wireless are considerably different so that the algorithms and protocols require some new and different forms from that of wireline networks (Katz, 1994) For example, the network algorithms to support wireless access are far more complex than for the wireline case; some of these are identified below. Whereas the location of a user or a device is a concern for wireline nets as described above, the details of tracking a user while moving in a wireless environment add to the complexity and require rules for handover, roaming, etc.

The cellular radio networks that are so prevalent today have an architecture that assumes the existence of a cell base station for each cell of the array; the base station controls the activity of its cell. The design considerations of such cellular networks are reasonably well understood and are being addressed by an entire industry (Padgett, et. al., 1995) We discuss these no further in this paper.[3]

There is however, another wireless networking architecture of interest which assumes no base stations (Alwan, et. al., 1996; Short, et. al. 1995). Such wireless networks are useful for applications that require "instant" infrastructure, among others. For example, disaster relief, emergency operations, special military operations, clandestine operations, etc., are all cases where no base station infrastructure can be assumed. In the case of no base stations, maintaining communications is considerably more difficult. For example, it may be the case that the destination for a given reception is not within range of the transmitter, in which case some form of relaying is required; this is known as *multi-hop* communications. Moreover, since there are no fixed location base stations, then the connectivity of the network is subject to considerable change as devices move around and/or as the medium changes its characteristics. A number of new considerations arise in these situations, and new kinds of network algorithms are needed to deal with them.

In order to elaborate on some of the issues with which one must be concerned in the case of no base stations, we decompose the possible scenarios into the following three:

4.1 Static Topology with One-Hop Communications

In this case, there is no motion among the system elements, and all transmitters can reach their destinations without any relays. The issues of concern, along with the needed network algorithms (shown in italics), are as follows:

- Can you reach your destination: *Power Control.*
- What access method should you use: *Network Access Control.*
- Which channel (or code) should you use: *Channel Assignment Control.*
- Will you interfere with another transmission: *Power and Medium Access Control.*
- When do you allow a new "call" into the system: *Admission Control.*
- For different multiplexed streams can you achieve the required QoS (e.g., bandwidth, loss, delay, delay jitter, higher order statistics, etc.): *Multimedia Control.*
- What packet size should you use: *System Design.*
- How are errors to be handled: *Error Control.*
- How do you handle congestion: *Congestion Control.*
- How do you adapt to failures: *Degradation Control.*

4.2 Static Topology with Multi-Hop Communications

Here the topology is static again, but transmitters may not be able to reach their destinations in one hop, and so multi-hop relay communications is necessary in some cases. The issues of concern, along with the needed network algorithms (shown in italics) are all of the above in Section 4.1, plus:

- Is there a path to your destination: *Path Control;*
- Does giant stepping (Takagi, et. al., 1984) help: *Power Control;*

[3] Wireless LANs come in a variety of forms. Some of them are centrally controlled, and therefore have some of the same control issues as cellular systems with base stations, while others have distributed control in which case they behave more like the no-base-station systems we discuss in this section.

- What routing procedure should you use: *Routing Control;*
- When should you reroute existing calls: *Reconfiguration Control;*
- How do you assign bandwidth and QoS along the path: *Admission Control and Channel Assignment.*

4.3 Dynamic Topology with Multi-Hop

In this case, the devices (radios, users, etc.) are allowed to move which causes the network connectivity to change dynamically. The issues of concern, along with the needed network algorithms (shown in italics) are all of the above in Sections 4.1 and 4.2, plus:

- Do you track, forward or search for your destination: *Location Control.*
- What network reconfiguration strategy should you use: *Adaptive Topology Control.*
- How should you use reconfigurable and adaptive base stations: *Adaptive Base Station Control.*

These lists of considerations are not complete, but are only illustrative of the many interesting research problems that present themselves in this environment. The net result of these considerations is that the typical 7-layer OSI model for networking must be modified to account for these new considerations. For example, we must ask what kind of Network Operating System (NOS) should be developed, along with other network functions (Short, et. al. 1995) What mobility modules must be introduced to support these new services, etc.

In this section we have addressed mainly the network algorithm issues, and have not focused on the many other issues involved with radio design, hardware design, tools for CAD, system drivers, etc. What is important is that the network algorithms must be supported by the underlying radio (e.g., to provide signal-to-interference ratios, ability to do power control, change codes in CDMA environments, etc.). These obviously have an impact on the functionality, structure and convenience of the appliance that the user must carry around, as well as on its cost.

5 ABOVE THE WIRELESS LAYER

We see from the previous sections that a number of algorithms must be developed to implement wireless networking, be it cellular or instant infrastructure. On the other hand the nomad may be connected via a modem, a LAN, an ATM connection, etc. Each of these access technologies requires different drivers, different configurations, different hardware, etc. It is highly desirable to shield the nomad from such differences to the extent possible. One way to accomplish this is to provide a standard interface protocol (such as TCP/IP) above which the system is basically unaware of the underlying communication substrate, and below which the system implements the necessary drivers, configuration, algorithms and hardware to support the various possible network technologies the nomad may encounter.

Another major development in nomadic computing involves the use of adaptive agents (also known as surrogates or proxies). The purpose of these agents is to carry out tasks on behalf of the nomad. For example, an adaptive agent may decide to send a low resolution black and white picture, or perhaps an outline of a document, to a nomad who is poorly connected, instead of a full resolution full color picture or the full document text. An adaptive agent can act as an “impedance match” between the network and the things attached to it. In general, they are there to support the nomad, the applications, the network, the servers, the communication devices and the computing devices.

6 CONCLUSION

In this paper we have presented nomadicity as a new paradigm in the use of computer and communications technology and have laid down a number of challenging problems. Nomadicity is an emerging fact of life, the needs of which are real, whose issues are fascinating, whose payoffs can be huge, and which makes all the problems we face in computing and communications harder. It is clear that our existing physical and logical infrastructure must be extended to support nomadicity in the many ways described above. The implication is that we must account for nomadicity at this early stage in the development and deployment of the Global Information Infrastructure; failure to do so will seriously inhibit the growth of nomadic computing and communications. In addition to those issues we raise in this paper, there are far more we have not yet identified, and those will only arise as we probe the frontiers of nomadic computing and communications. One should not and cannot ignore the challenge of nomadicity.

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