Rapidly Deployable Radio Network: Semi-Annual Technical Report

K. Sam Shanmugan
Victor S. Frost
Joseph B. Evans
Glenn Prescott
Richard Plumb
David W. Petr

TISL Technical Report TISL-10920-08

June 15, 1995

TISL

Telecommunications and Information Sciences Laboratory
The University of Kansas Center for Research, Inc.
2291 Irving Hill Drive Lawrence, Kansas 66045

Rapidly Deployable Radio Network: Semi-Annual Technical Report

K. Sam Shanmugan
Victor S. Frost
Joseph B. Evans
Glenn Prescott
Richard Plumb
David W. Petr

TISL Technical Report TISL-10920-08
Telecommunications and Information Sciences Laboratory
Electrical Engineering and Computer Science
University of Kansas
http://www.tisl.ukans.edu/

Sponsored by:
Defense Advanced Research Projects Agency/CSTO
AARPA Order No. 8195
Issued Contract #J-FBI-94-223

June 15, 1995

Contents

Figures

Abstract

An architecture to provide high-performance end-to-end wireless communications is being developed. Key aspects of the architecture will be implemented and demonstrated. The systems will use ATM technology and be adaptive at both the link and network levels to allow for rapid deployment and response to a changing environment. This report discusses progress to date, including the architecture and definition of the prototype that is under development, as well as an innovative approach for adaptive beamforming. Additional information about this project can be found at http://www.tisl.ukans.edu/RDRN/.

1.0 Summary

1.1 Project Goals

The goal of this effort is to create a high-speed ATM-based wireless communication system that will be adaptive at both the link and network levels to allow for rapid deployment and response to a changing environment. The objective of the architecture is to use an adaptive point-to-point topology to gain the advantages of ATM for wireless networks. This effort is significant because it will demonstrate greater than 1 Mb/s throughputs to wireless users at distances of 3 to 10 km using Internet, ATM, and industry standards-based information infrastructure.

1.2 Major Accomplishments 9/30/94 - 5/31/95

- Developed and validated a transmit antenna pointing technique that combines beamforming and digital modulation.
- Developed and implemented the low-bandwidth, low-power, omni-directional radio network (orderwire) that will be used for location determination, switch coordination, and management.
- Developed and implemented a network configuration algorithm using a *consistent labeling* model. The algorithm produces a list of acceptable switch-to-switch configurations given a set of constraints.
- Developed an architecture for an ATM-based wireless communication system and a detailed prototype implementation plan.

1.3 Anticipated Milestones 6/1/95 - 12/31/95

- Demonstration of interactive real-time applications, e.g., Internet voice and video, using a prototype system. This phase of the prototype system will include antenna pointing based on GPS information and interworking between wired and wireless end users.
- Determine a detailed link budget including the mobile RDRN channel fade margin and investigate the RDRN channel itself, including the effects of the RDRN antenna pattern.
- Assess the performance of forward error correction for RDRN.
- Develop an efficient algorithm that determines which end users associated with a switch will share each antenna beam. The algorithm will also determine an exact beam angle for each cluster of users. The goal will be to maximize the minimum signal-to-interference ratio experienced by the set of end users.

2.0 Background

The goal of this research is to conduct a detailed system design of a high-capacity communication network suitable for rapid deployment. Key elements of this system will be implemented to prove the viability of the concept. The system will be adaptable to its environment and automatically configure itself into a high-capacity, fault tolerant, reliable network. No central controller or management center will be required. As shown in Figure 2.1, the architecture is composed of three overlaid networks: 1) a low-bandwidth, low-power, omni-directional network for location determination, switch coordination, and management; 2) a "cellular-like" system for multiple end user access to the switch; and 3) a high-capacity, highly directional, multiple beam network for switch-to-switch communication.

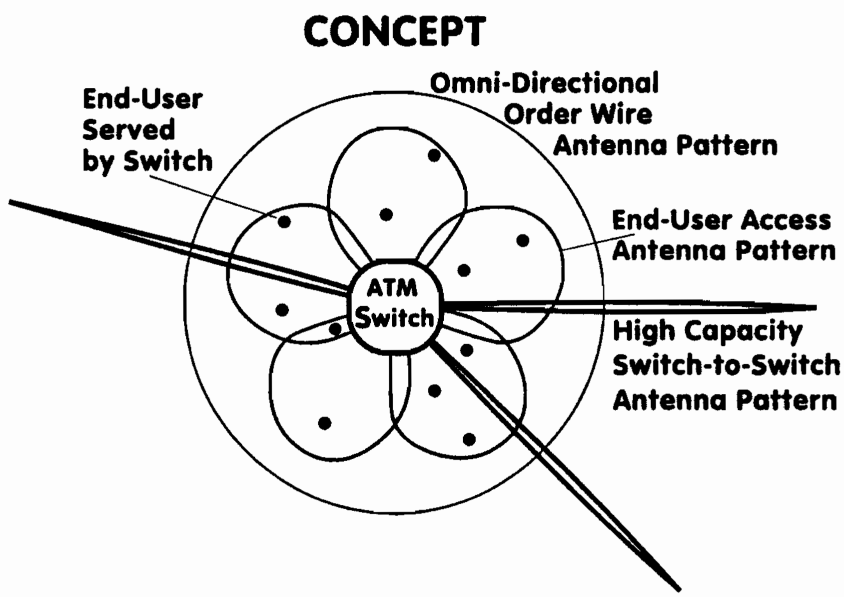

Figure 2.1. System Concept

Network elements are adaptable and programmable and contain a phased array steerable antenna and a communication network controller. As part of this approach, the system initiates three activities: 1) determines its location via the Global Positioning System (GPS) and begins broadcasting its location on a low-capacity channel; 2) listens for other network elements broadcasting their locations; and 3) monitors the radio frequency environment to detect other communication nodes or interfering signals. As other nearby switches are detected, the local switch establishes a high-capacity point-to-point RF link to these nearby nodes. Link coordination takes place over the low-capacity, omni-directional link, while the local antenna is configured to steer its beams toward nearby switches, establishing the high-capacity links. The use of point-to-point links means that link throughput can be maximized and frequencies can be reused on a regular, spatial basis.

Spatial reuse also will be exploited for end user/switch communications. Continuous knowledge of the location of all the network elements using GPS will aid this architecture in providing smooth call hand-off. The system will have the capability to predict when a hand-off event should occur, plan for that event, and smoothly execute the hand-off. When hand-offs occur, all virtual circuits connected to the end user will be seamlessly switched. An innovative aspect of this effort is the use of GPS-derived location information for antenna beamforming, network management, and control, and the extensive use of digital signal processing technology for implementing the radio signal processing functions.

Should a link between two nodes be broken due to equipment failure, link degradation, or one of the nodes simply moving out of range, the network controllers detect this topology change and initiate a reconfiguration of the network topology. The reconfiguration is carried out automatically in a distributed manner.

The network elements used in this effort will support virtual circuits based on Broadband Integrated Services Digital Network (B-ISDN) concepts, in particular, the ATM protocols. This means that communication nodes are compatible with the evolving telecommunications infrastructure. The use of standards-based ATM technology allows for the seamless integration of the wireless network into existing systems and the subsequent potential for large scale wired/wireless networking.

3.0 Accomplishments

This section provides additional details on each accomplishment from September 30, 1994, to May 31, 1995.

3.1 Architectural Overview and Prototype Implementation Plan

To achieve the goals for RDRN, an architecture composed of 1) antenna beamforming, 2) adaptive radio links, 3) network protocols and call management, and 4) network configuration/reconfiguration algorithms is being developed.

Antenna beamforming provides for spatial reuse. Complex adaptive algorithms are not required because the GPS is used to learn the location of all network elements. Location as well as link quality information is distributed via an out-of-band mechanism, an orderwire network. Details of the antenna beamforming algorithm are given in Section 3.4, while additional information on the orderwire network is provided in Section 3.3.

The radio link research in RDRN will focus on fully programmable and adaptive systems that will continually monitor key parameters of the RF environment, such as the received signal strength, signal quality, and propagation conditions, and select an appropriate data rate as well as modulation, coding, diversity, and equalization schemes. Implementing the signal processing algorithms on an array of programmable DSP processors such as the TI TMS320-C40s may enable the development of a fully programmable adaptive radio.

To ensure the seamless integration of RDRN into the existing information infrastructure, standards-based network protocols and call management are being used whenever possible. Toward this end, RDRN strives to make the wireless environment 'look like' an ATM system. The system connects wireless end users to the switch via 'ports' where a 'port' consists of a Time Slot (or CDMA code), antenna phase (pointing), link quality, and frequency that defines the physical connection between the switch and the end user. The orderwire system is responsible for establishing the port assignments. Once the physical connections are established via the ports, ATM signaling is used to set up an ATM VC. This process assigns a mapping between a VCI and a port. IP over ATM mechanisms are then used to set up the communications between end user processes. Thus, the physical layer is wireless for the end users and ATM/SONET for WAN transport. An HDLC-like protocol will be used over the wireless links with multiple ATM cells contained in each HDLC frame to form the data link layer. Using ATM on the wireless segment of RDRN will enable the use of knowledge of ATM Quality of Service parameters to increase the efficiency of the link. For example, errored real-time traffic will not be retransmitted. Wireless ATM also preserves some of the benefits of cut-through switching, e.g., frames on the wireless link will contain 20-40 cells, while it is common for AAL5 protocol data units to contain more than 150 cells. ATM call processing will be used to establish end-to-end connections, and IP techniques will be used for addressing and routing.

Network configuration/reconfiguration occurs at two levels. At the lowest level, the radios must configure themselves to communicate with each other. Also, the ATM switches must learn the network topology in order to properly switch cells. The ATM configuration algorithm (based on the DEC AutoNet system) is composed of two phases: monitoring and topology acquisition. The monitoring algorithm watches links for changes in up/down status. It incorporates a mechanism for damping oscillations between states, which will be useful in a radio environment. The topology acquisition phase propagates neighborhood information from each switch to a root node, which then distributes the result back to all nodes. A mechanism is included to handle recurrent topology changes. The latest change is given priority; thus, earlier propagation phases die out before the latest one ends. The interaction between these two tasks in a remote environment is under study.

To demonstrate the major elements of RDRN, a prototype system consisting of two types of nodes (a remote node and an edge interface node) will be constructed, as shown in Figure 3.1.

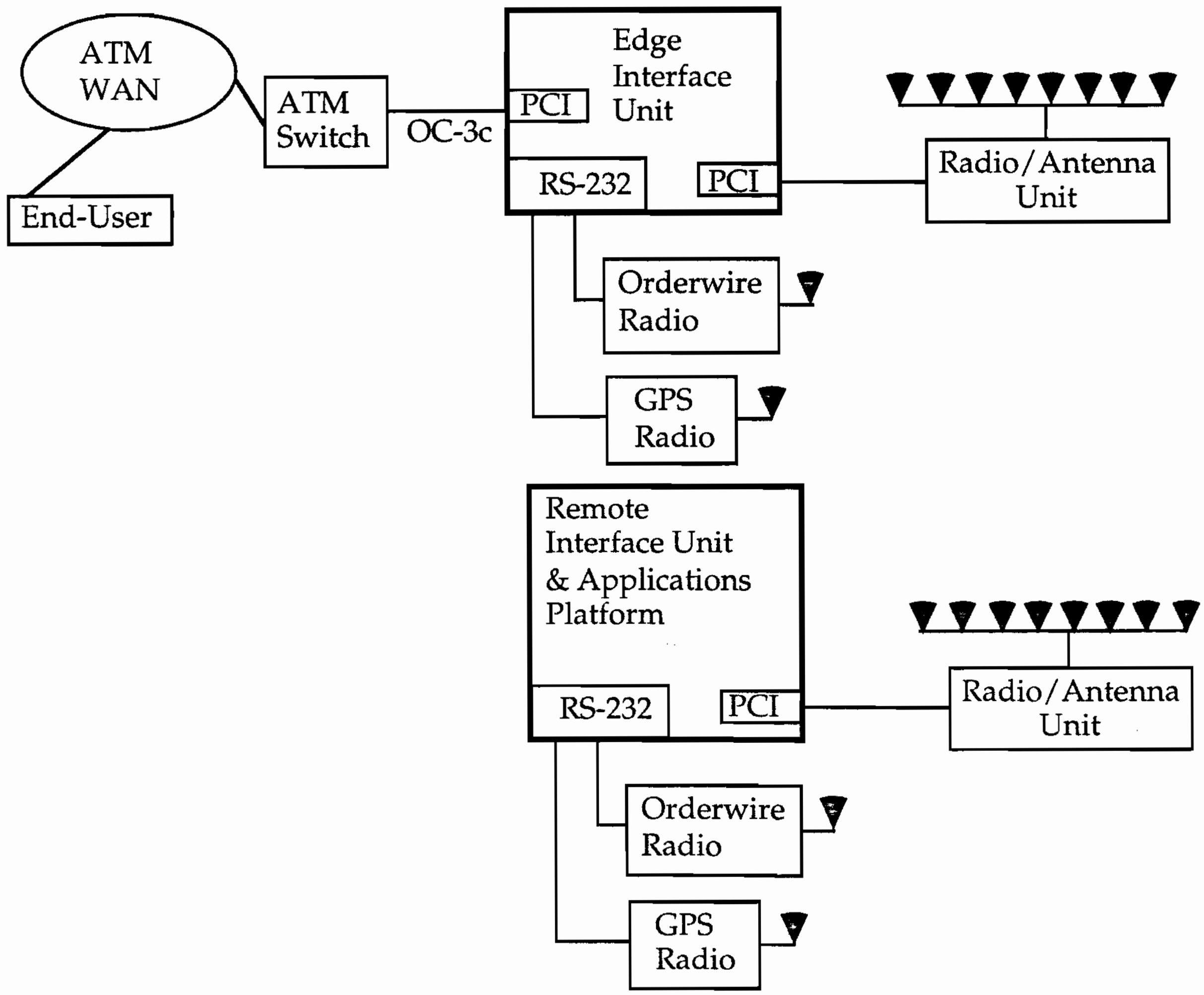

Figure 3.1. Initial RDRN Prototype System

A remote node will consist of a Pentium-based computer system (PC) with a PCI bus. The PC will have a PCI host interface card and a serial interface to an orderwire modem and the GPS receiver. The host interface card will have a shielded cable that will extend out to an antenna/radio system housed in a VME-type rack. This rack will contain a Rack Control Card that will serve as an interface to the host, an Oscillator Card that will contain and distribute the RF/IF oscillators, a QPSK Receiver Card, and eight Transmit Beamforming Cards. Each Transmit Beamforming Card will drive a single element of an eight-element transmit antenna. The antennas will be mounted on top of a ground plane attached to the rack. Initially, a single omni-directional receive antenna will also be used. An edge interface unit will contain everything the remote node has and a PCI-based OC-3 ATM network card. The initial prototype will use a commercial ATM card and perform the cell processing and bridging from the ATM card to the radio interface in a software device driver. The initial software interface will allow for the rapid prototyping of the operation of the system and ease the testing of the radio portions of the design. The prototype system will allow for four independent antenna beams; within each beam 2 Mb/s can be transmitted. The digital beamforming will be done in the transmit direction at baseband in the prototype by the use of off-line floating point calculation for the phasing information, using lookup tables for each array element (see Section 3.4 for details of the beamforming strategy). The lookup tables allow both beam steering and the placement of nulls, since we have full control of phase and amplitude at each element and therefore control of the steering angle and amplitude of each beam. The radio link for the prototype will have a fixed QPSK modulation. The link will be TDMA within a beam, although a single user can negotiate for all the available bandwidth (2 Mb/s) at call setup time if the resources are available. Adaptive forward error correction coding schemes will be supported. Adaptive power control is also supported. Call management and protocol research will be supported by an orderwire network in the prototype. The orderwire is a 430 MHz broadcast system based on a 19.2 kb/s AX.25 packet radio network. Link quality reports and physical location information will be sent, and physical port assignments will be received by remote nodes. Network configuration/reconfiguration will be demonstrated with this prototype. The system will demonstrate hand-off algorithms using the orderwire network and port and resource assignment, as well as algorithms for automatic network configuration/reconfiguration.

3.2 An Algorithm to Determine Constrained RDRN Configurations

The RDRN architecture assumes the use of directional antennas, which presents new constraints on network configurations. The problem addressed here is how to assign resources, for example frequencies and CDMA codes, to minimize interference. This problem has been successfully addressed using a consistent labeling (U, L, T, R) model.

For the RDRN application, U consists of all links that could exist between nodes. For each node, all nodes within a specified maximum connecting distance, known as the linking radius, are found. These combinations of pairs constitute U. All frequency/code permutation pairs with the option of zero, or no link, constitute L, the set of labels. The unit constraint relation, $T \subseteq U^N$, consists of those pairs of units (links) that mutually constrain one another. If two links have the potential of interfering with each other, then they are a pair in T. The unit-label constraint relation, $R \subseteq (UxL)^N$, contains all permitted labeling of the pairs within T. For RDRN, R contains all the frequency/code labelings for the pairs of nodes in T that would not cause interference between them. The consistent labeling problem is to find all the permitted labelings of the units in U that are allowable by T and R.

Creating the consistent labeling model for RDRN requires the examination of several rules or constraints. The first restriction placed on the network is that nodes can only form links within their given transmission radius. This limitation influences the creation of the unit vector U. Second, two links will constrain each other if the transmission pattern from a node in the first link can be received by a node in the second link or vice versa. An example of this is shown in Figure 3.2.

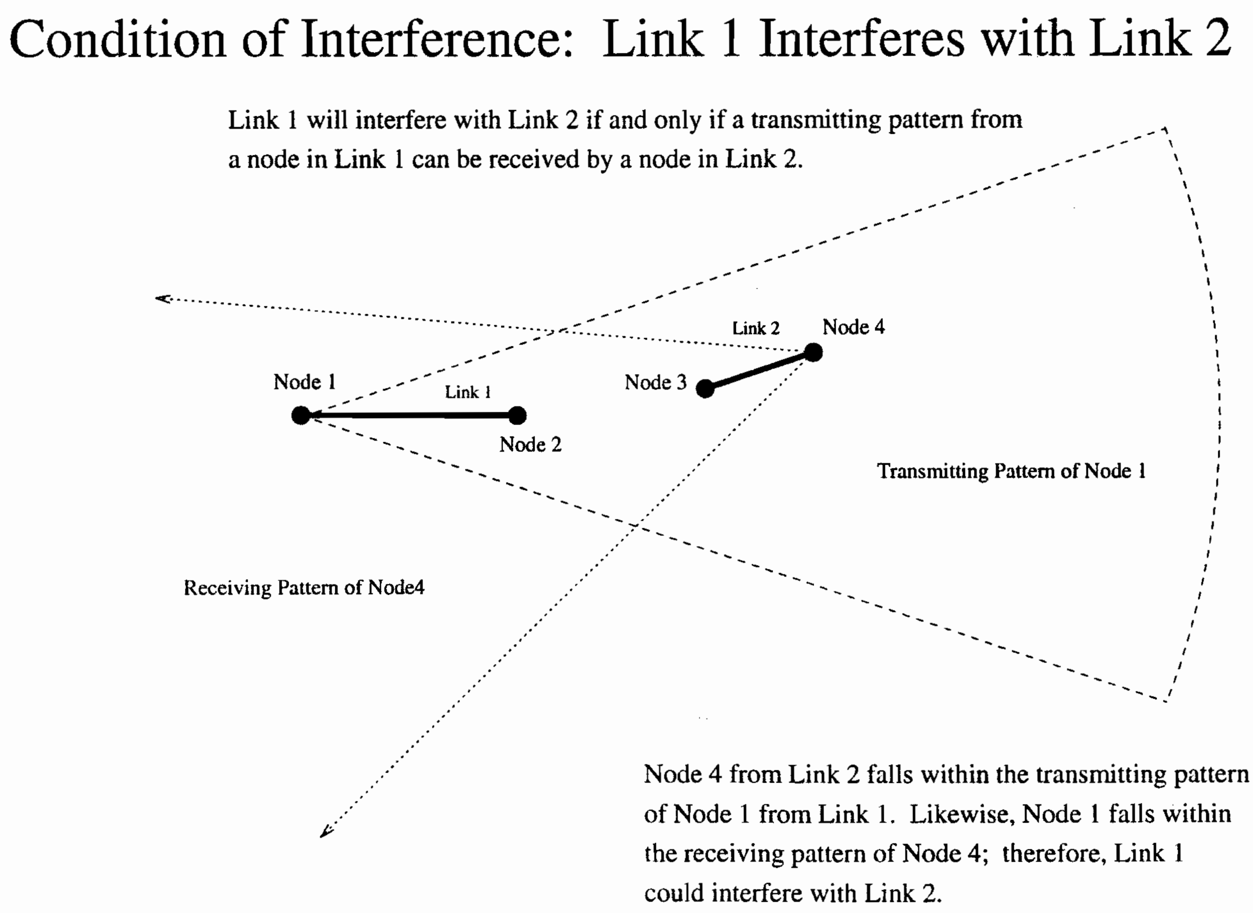

Figure 3.2. Link 1 Could Interfere With Link 2

The unit constraint relation T is created on this principle. Third, if two links constrain each other, frequency/code labels must be assigned in such a way as to avoid interference. The unit label constraint relation R contains all of these permitted link/labeling 4-tuples. By describing RDRN using a consistent labeling (U, L, T, R) model, a tree search can be used to find the non-interfering network configurations. This does not, however, guarantee full network communication. A connectivity matrix is created, showing direct node communications. Another tree search is then used to find communication classes of this matrix. In this manner, network connectivity may be tested.

The consistent labeling model for RDRN has been implemented and tested to find the set of minimally interfering network configurations for an arbitrary set of nodes. Three basic steps are required to solve this interference topology problem: 1) defining node coordinates; 2) creating the (U, L, T, R) model; and 3) finding acceptable network configurations. A tool has been implemented to facilitate executing these steps. In the implementation, these steps can be entered as text commands, selected from a graphic user interface (GUI), or a combination of both.

There are several ways in which the efficiency of these algorithms may be enhanced. First, by using a concept similar to the connectivity matrix, the entire consistent labeling problem may be broken down into several smaller ones. Second, links essential for connectivity may be identified. Finally, a faster programming language could be used.

The consistent labeling theory has been applied to solve the frequency-code assignment problem in RDRN. A tool has been developed to facilitate its use to solve resource assignment problems in networks that use directional antennas.

3.3 Orderwire Subsystem

The orderwire system provides an out-of-band mechanism to distribute location and link quality information. The orderwire is a 430 MHz broadcast system based on a 19.2 kb/s AX.25 packet radio network. The initial version of the orderwire protocols has been emulated using the system shown in Figure 3.3.

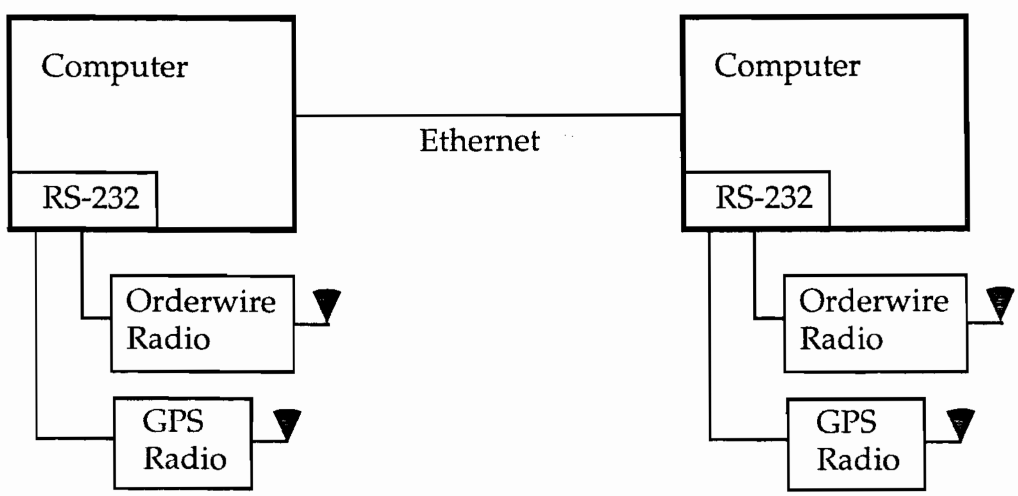

Figure 3.3. Orderwire Emulation System

In this emulation, the Ethernet plays the role of the high-speed radio link. Procedures have been developed and implemented to establish both switch-to-switch and switch-to-user connections. The orderwire emulation is a useful way to design and test the high-speed port configuration protocol using the actual orderwire packet radios and GPS systems. The initial protocol and packet structure were defined using Maisie, a public domain distributed simulation tool. Those results were further refined using this emulation. In the emulation, a TCP/IP connection is established by the orderwire in which a TCP socket represents an ATM VCI/port mapping. The software that handles the processing of GPS information supports actual or simulated GPS data. Thus movement and handoff of remote nodes can be emulated as well. A packet structure and protocol have been designed and validated using this emulation.

An experiment was conducted to validate the location tracking capability of this system. For this test, one unit (computer, GPS receiver, and radio) was placed on the roof of Nichols Hall on the KU campus, while the other unit was made remote by placing it in a car and driving it around Lawrence, Kansas. The result is shown, overlaid on a map, in Figure 3.4. The GPS receiver used in this system outputs its position once every second. Only one of every ten position updates was transmitted, and each successful reception is represented by a solid black circle on the map.

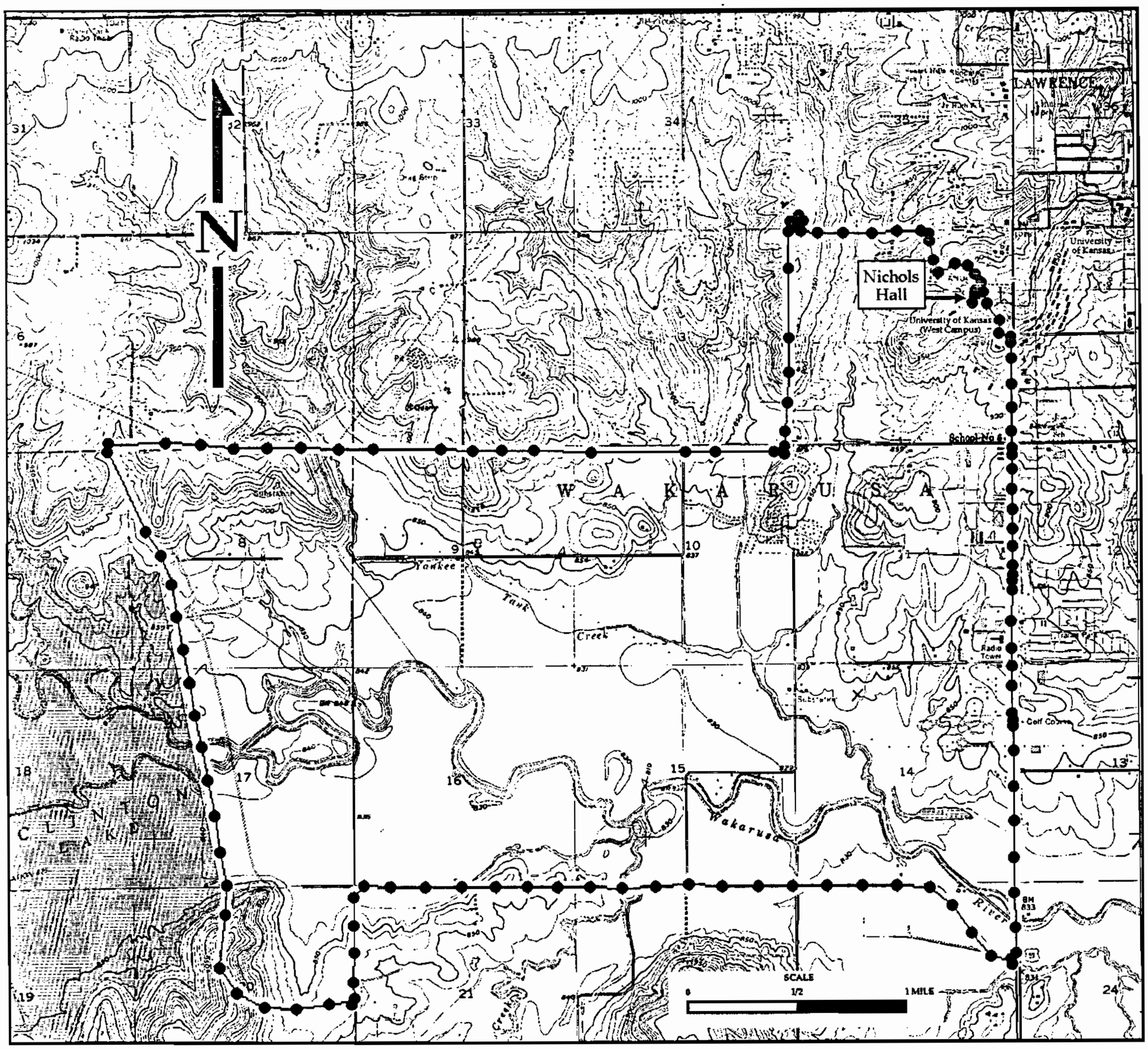

Figure 3.4. GPS and Packet Radio Test

The GPS receiver is a Garmin GPS 10-05. The packet radio consists of a Kantronics D4-10 radio and Kantronics Data Engine (modem). A Motorola HC11 microcontroller was used to automate and run the mobile system. It was responsible for parsing the data coming from the GPS receiver and sending the time, latitude, and longitude to the data engine for transmission.

3.4 Transmit Antenna Beamforming

The key points in the transmit antenna beamforming subsystem are:

- Beamforming is done digitally at baseband by changing the relative phases of each user's signal that is ultimately sent to each element of the array antenna.

- The digital modulation technique used is not limited to any specific method, even though in the prototype design we opted to use QPSK.

- The required phase and amplitude for each antenna element (and each beam) are calculated "off-line" and programmed into memory modules that can be addressed by the I and Q channels of the QPSK modulator.

The transmitter block diagram is shown in Figure 3.5. The users are assigned to beams based on their location. The algorithm to optimally achieve this assignment is under development. Based on this information, the relative phase and amplitude of each beam and antenna element combination are computed.

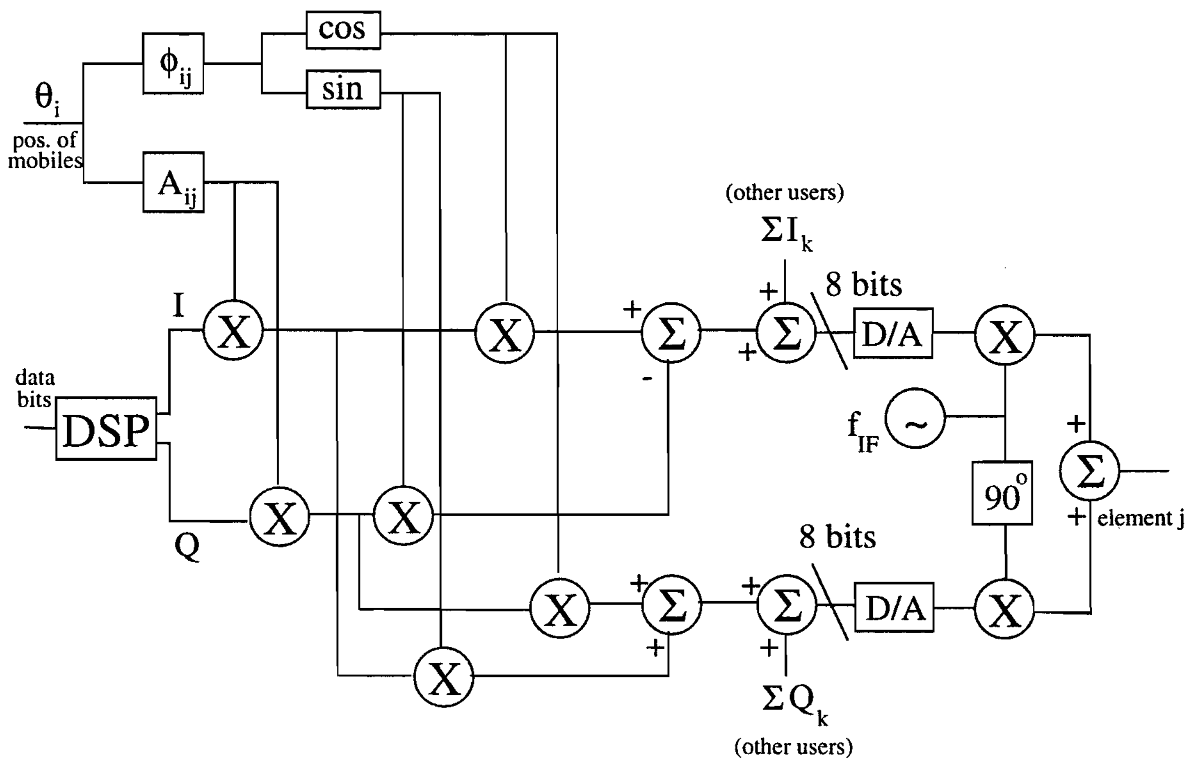

Figure 3.5. RDRN Transmitter Implementation

Digital beamforming is achieved by changing the phase of the equivalent baseband complex signal that is given in terms of the in-phase (I) and quadrature (Q) channels. Let $x(t)=I+jQ$ represent the complex baseband signal. Then

$$X(t)=x(t)Ae^{j\phi}$$

represents the complex baseband signal that has a relative amplitude A and phase ϕ associated with it. These changes then modify the carrier signal amplitude and phase since

$$\mathrm{Re}\left[X(t)e^{j2\pi f_c t}\right]=\mathrm{Re}\left[x(t)\left(Ae^{j2\pi f_c t+j\phi}\right)\right].$$

In our implementation, instead of generating the sine and cosine values of the phases of each user and antenna element combination, we use a look-up table as described later. The aggregate in-phase (M) and quadrature (N) signals that modulate the signal for each element can be written as

$$\begin{aligned} M_j &= \sum_i \left[I_i A_{ij}\cos\left(\phi_{ij}\right)-Q_i A_{ij}\sin\left(\phi_{ij}\right)\right] \\ N_j &= \sum_i \left[I_i A_{ij}\sin\left(\phi_{ij}\right)+Q_i A_{ij}\cos\left(\phi_{ij}\right)\right] \end{aligned} \qquad (1)$$

where the index i represents the user and index j refers to a particular antenna element. Note that for all users in a single beam, the values of A_{ij} and ϕ_{ij} are the same.

Any digital modulation may be used with this digital beamforming technique. Let the baseband signal be represented by

$$s=\sum_{n=0}^{\infty}u(t-nT)$$

where u(t) is the baseband pulse shape corresponding to the information symbol at time t. S is assumed to include the time index t implicitly. The most general form of modulation can be expressed as

$$x(t)=\mathrm{Re}\left[\alpha(s)\exp\left(j2\pi f_c t+\phi_0+\Phi(s)\right)\right]$$

where $\alpha(s)$ represents any form of amplitude modulation, f_c is the carrier frequency, ϕ_0 is an initial phase, and $\Phi(s)$ represents any form of phase modulation. In most modulation schemes, $\alpha(s)$ will reduce to $\alpha(u(t))$ where t represents the current time index or, in phase shift keying, further reduce to a constant α. $\Phi(s)$ can represent Continuous Phase Frequency Shift Keying (CPFSK) schemes, of which Minimum Shift Keying (MSK) is a special case. It can also represent all Phase Shift Keying methods where the dependency reduces to $\Phi(u(t))$, or even coded modulation schemes like Trellis Coded Modulation (TCM). Digital beamforming introduces an additional relative phase and amplitude of the signal going to each antenna element. Thus, the digitally modulated signal of a single user which is just $x_i(t)$ is modified to

$$x_{ij}(t)=\mathrm{Re}\left[A_{ij}(t)\exp\left(j\phi_{ij}(t)\right)\alpha_i(s_i)\exp\left(j2\pi f_c t+\Phi(s_i)\right)\right]$$

where subscript i refers to a user index and j refers to a specific element of the phased array antenna. The initial phase ϕ_0 is not shown explicitly above. Since the remote unit may travel at low speeds, $A_{ij}(t)$ and $\phi_{ij}(t)$ are slowly changing functions (as compared to $\alpha_i(s_i)$ or $\Phi(s_i)$). Thus, the aggregate signal coming to an element is given by

$$S_j(t) = \sum_i \mathrm{Re}\left[A_{ij}(t)\exp\left(j\phi_{ij}(t)\right)\alpha_i(s_i)\exp\left(j2\pi f_c t + \Phi(s_i)\right)\right].$$

For MPSK and QAM this form of digital beamforming may be efficiently implemented using a table look-up approach. It is clear that only the in-phase and quadrature bits I_i and Q_i change at the information bit rate. All the other quantities change over a much longer duration. In the prototype design up to four beams are allowed, so there are only eight bits (I_1, Q_1, I_2, Q_2, I_3, Q_3, I_4, Q_4) that change at the information bit rate. Thus, in general, for N_b beams only $2N_b$ bits are required to address the memory module containing the quantized sum from equation (1). The prototype implementation uses the eight bits to address a memory module that stores the corresponding sum given in equation (1). Two such memory modules are used for each antenna element j, one for M_j and one for N_j. These memory modules need to be updated periodically so that the relative phases are consistent with the motion of the mobile user. This is accomplished by using a "hot" and a "cold" memory module instead of a single one so that at any time the hot module is being used while the cold module is in the updating state. The updating is performed "off-line."

A simulation study was performed to validate this approach and evaluate the effects of using a finite number of bits to represent the signal used as input to the D/A blocks shown in Figure 3.5. The simulation results indicated a need for an E_b/N_0 of 11 dB and at least six bits of quantization to achieve a bit error probability of 10^{-6} assuming a minimum of 30 degree beam separation, nine-element phased array antenna, no coding, QPSK modulation, and white Gaussian noise channel. The study also validated several concepts used in this architecture. These include digital beamforming and the flexibility in modulation. It is seen that the beamforming approach does not limit us to any specific modulation scheme and thus in future it may be used for more complex schemes such as MSK or trellis coded modulation.

4.0 Technology Transfer

Sprint Corp., Overland Park, Kansas, is providing support to construct additional prototype systems and conduct a demonstration prototype over the ACTS ATM Internetwork. Their effort will be implemented in three phases over a three-year period (funding for year one is currently in place). In the first year a prototype wire/wireless network will be implemented and demonstrated given the configuration shown in Figure 4.1.

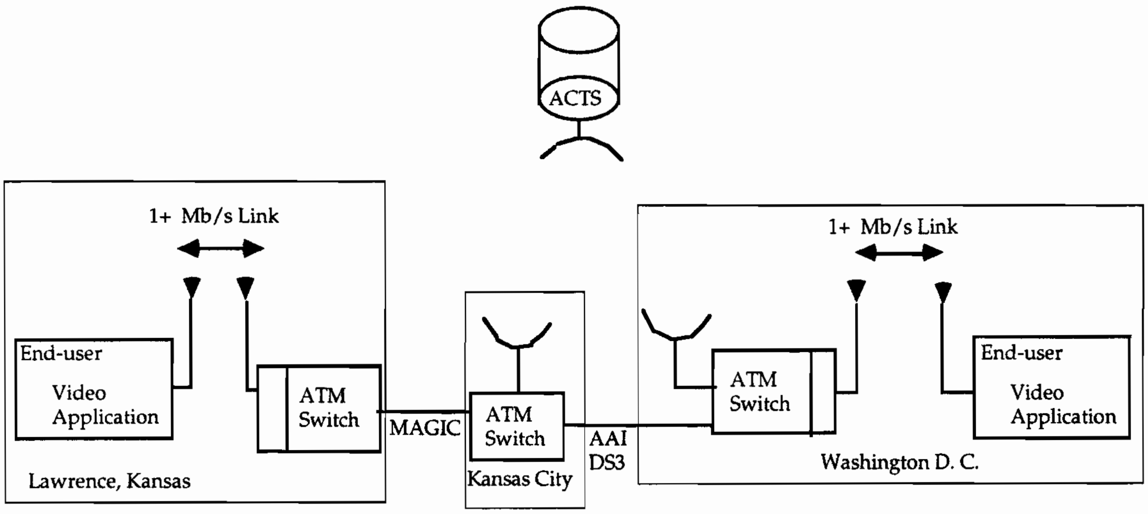

Figure 4.1. Demonstration Configuration

For this effort, equipment supporting one wireless end user will be implemented for each location. For the Washington location, KU will provide the end user node and the interface to an ATM switch. The ATM switch is assumed to have an OC-3c port for the wireless connection and interfaces for the ACTS and/or AAI DS3 links. These devices will not be provided by KU. Two demonstrations of this network will be conducted. These events will show two applications: 1) a video session between the wireless end users; and 2) the TerraVision tile browser. During the first year, mobile-IP issues will also be investigated.

The second year of the effort (if funded) will focus on mobile-IP issues as well as network management for the wireless environment. Prototype implementation of mobile-IP and interfaces between the wireless ATM network and a management system will be demonstrated by the end of the second year. The focus of the third year (if funded) will be on performance characterization and enhancements of the wire/wireless network.

5.0 RDRN Staff and Associated Personnel

Principal Investigator	Dr. K. Sam Shanmugan	shanmugan@eecs.ukans.edu or shanmuga@csi.com 913-864-4831(voice) 913-864-7789(fax)
Co- Investigator	Dr. Victor Frost	frost@eecs.ukans.edu
Co- Investigator	Dr. Joseph Evans	evans@eecs.ukans.edu
Co- Investigator	Dr. Glenn Prescott	prescott@eecs.ukans.edu
Co- Investigator	Dr. David Petr	dwp@eecs.ukans.edu
Co- Investigator	Dr. Richard Plumb	plumb@eecs.ukans.edu
Research Associate	Dr. Srinivas Sivaprakasam	srinivas@tisl.ukans.edu
Research Associate	Ben Ewy	bewy@tisl.ukans.edu
Graduate Research Assistant	Craig Sparks	sparks@tisl.ukans.edu
Graduate Research Assistant	Nathan Goodman	ngoodman@tisl.ukans.edu
Graduate Research Assistant	Sunil Jagannath	sunil@tisl.ukans.edu
Graduate Research Assistant	Steve Bush	sbush@tisl.ukans.edu
Undergraduate Research Assistant	Shane Haas	shaas@tisl.ukans.edu
Undergraduate Research Assistant	Harvind Samra	samra@tisl.ukans.edu
Administrative Contact	Barbara Armbrister	BJA3444@kuhub.cc.ukans.edu 913-864-3444(voice) 913-864-7789(fax)
Media Relations Contact	John Francis	jfrancis@kuhub.cc.ukans.edu 913-864-3881(voice) 913-864-5445(fax)

Appendix A

A Consistent Labeling Algorithm for Frequency/Code Assignment in RDRN