

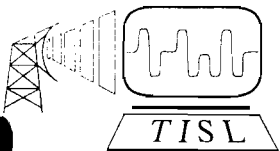
An Overview of the Rapidly Deployable Radio Network Proof of Concept System

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AN OVERVIEW OF THE RAPIDLY DEPLOYABLE RADIO NETWORK PROOF OF CONCEPT SYSTEM

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1. INTRODUCTION

The primary goal of the Rapidly Deployable Radio Network (RDRN) project is to develop a high speed Asynchronous Transfer Mode based wireless communication system that is adaptive at both the link and network levels to allow for rapid deployment and to respond to a changing environment. The RDRN proof of concept system provides a test-bed for the development of wireless ATM protocols, advanced network configuration algorithms, and adaptive software controlled radios.

The prototype system allows mobile nodes equipped with a Global Positioning System (GPS) receiver, a packet radio system used for out-of-band signaling, and a wireless ATM interface to integrate seamlessly with an end-to-end ATM Wide Area Network (WAN).

Antenna beamforming is performed to allow for spatial reuse of the transmission frequencies being used. Location, link quality, and call management information are passed using the out-of-band order wire network. A flexible transmitter takes advantage of the location information to steer beams to each mobile node. The link quality is monitored and modulation schemes, data rates, frame sizes, frequencies, power levels, and coding schemes can be rapidly adapted to suite the changing propagation environment.

The major elements implemented in the proof of concept system are adaptive digital beamforming, an ATM based radio link, a call management and network protocol implementation, and automatic network configuration/reconfiguration. Ongoing research focuses on managing the adaptive nature of the network, conformal antenna arrays, and flexible digital beamforming in the receive direction. This paper begins with an overview of the RDRN system. The implementation of key features and how they address the design goals and constraints of our system are discussed in detail. Finally, preliminary results are presented and future directions outlined.

2. THE SYSTEM OVERVIEW

The prototype system is designed to allow remote users to connect to a fiber based ATM network over a reconfigurable wireless ATM based network. Figure 1 shows a typical network based on the prototype system. Multiple remote nodes use the edge switch for interconnection to each other and to the WAN. The edge switch is an ATM switch with one fiber based OC-3 ATM port and a variable number of virtual ports that connect to the adaptive wireless network. The edge switch is able to generate multiple digitally formed beams

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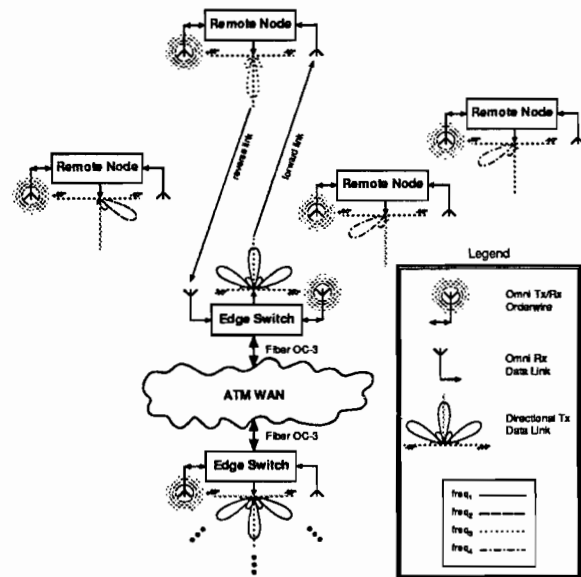


Figure 1. RDRN Radio Network

each of which can have independent modulation schemes. As implemented, depending on the modulation scheme chosen for a given beam, a 1 to 2 Mbps data rate can be partitioned using a TDMA structure to support as many as 64 users per beam. Alternatively, a single node can arbitrate for all of the bandwidth available in a particular beam.

The multiple beams formed by a specific transmitter are all of the same center frequency, demonstrating spatial frequency reuse. This prototype system only addresses beamforming in the transmit direction, leaving beamforming receivers for future research, therefore, each of the remote nodes communicates back to the edge switch using unique frequencies.

Each of the nodes has a GPS receiver, and a low speed 19,200 bps packet radio. The packet radio is used as the basis of an order wire network, to exchange position information and network status messages. The edge switch uses the position updates from the GPS receiver to steer the beams as the remote nodes move. Both the remote nodes and the edge switch use an eight element antenna array to form beams in the transmit direction, and have an omni directional receive antenna.

Network configuration/reconfiguration algorithms are implemented in the prototype. The system demonstrates hand-off algorithms using the order-wire network, port and resource assignment, and automatic network configu-

ration/reconfiguration.

The wireless ATM network supports ATM signaling and makes use of ATM quality of service parameters at the link level. At call setup time, the order wire network is used to determine link parameters such as modulation scheme, frequency, and beam direction to the edge switch. As packets pass down the traditional network protocol stack they are segmented into ATM Adaptation Layer 5 (AAL5) packets and passed to the wireless data link layer. The wireless data link layer supports the adaptive management of frames sent over the wireless link. Routing information is used to determine which beam a packet is destined for. Queues are built for each beam based on priority and traffic class. Different types of data link layer protocols are used for the different queues. AAL5 type data traffic is sent using an adaptive stop and wait protocol. Constant Bit Rate (CBR) type traffic is sent with highest priority but without regard to its reception. This system allows the ATM quality of service classes to be preserved over the wireless link. The ATM cells for a given queue are then encapsulated within a wireless data frame.

3. SYSTEM ARCHITECTURE

Our proof of concept system has been designed to provide a number of features and support research into several key areas. These include:

- Demonstration of a Wireless ATM Network
- Demonstration of Digital Beamforming
- Support Research into Adaptive Software Controlled Radios
- Demonstration of Automatic Network Configuration/Reconfiguration
- Demonstrate interoperability with existing standardized ATM infrastructure

3.1. Wireless ATM Network

The proof of concept system allows multiple remote nodes to move within a 10 km range of an edge switch that serves as a base station for the mobile nodes. The Amateur Radio Service (ARS) frequency band from 1240 - 1300 Mhz was chosen for our proof of concept system to allow ease of testing within relatively open regulations. The bandwidth of each beam is currently constrained by the available continuous spectrum to 1 MSymbols/sec, with symbol rates up to 10 MSymbols/sec possible with the current host and switch hardware and modified RF components as needed for the alternate frequency ranges. Multiple remote nodes assigned to an edge switch are supported through two methods, multiple independent beams of the same frequency can be formed if the remote nodes are geographically separated enough so that there is not interference, or they can be grouped into the same beam using a TDMA system. Every remote node has a GPS receiver that it uses for position information for the steering of the beams and it uses a GPS time synchronization pulse to partition time into maximal frame length time increments. The clocks are synchronized to within 2 us and guard bands are allotted to compensate for this variation and the different propagation times from nodes at different distances. The time slots can be allocated as a schedule to support flexible bandwidth allocation and to support a more uniform arrival of frames to reduce the burstiness of traffic destined for the WAN.

The demonstration system is a tool for the research into different forms of Forward Error Correction (FEC) coding, interleaving, and modulations. One important design goal was to have enough excess link budget so that links could be established with an acceptable error rate without relying on a particular method to compensate for real world channels. A Bit Error Rate (BER) of no less than 10^{-5} was chosen as a minimum acceptable BER without any coding.

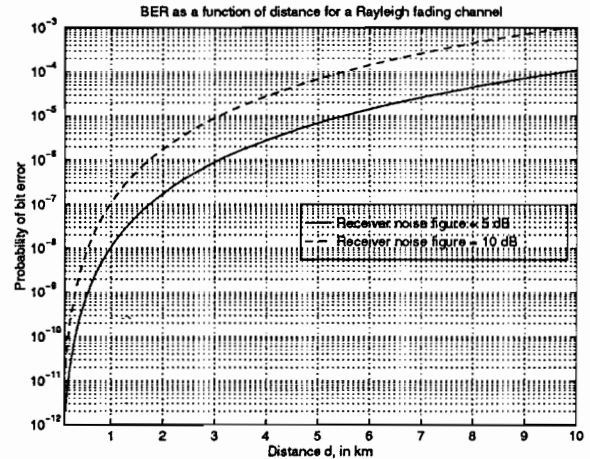


Figure 2. BER vs Distance in Rayleigh Fading Channel

A link budget analysis was completed[5] that took into account the parameters of our system including approximately 5 W of transmit power being available. Figure 2 shows the BER as a function of distance for a system without coding or interleaving in a Rayleigh fading channel for two representative receiver noise figures. This performance allows a great deal of flexibility for experimenting with FEC coding schemes and interleaving sizes without being locked into one particular method to simply close the link in a non ideal channel.

Using the BER's calculated, the frame size that was found most appropriate for a stop and wait protocol was approximately 200 bytes. Figure 3 shows the wireless data frame structure. The length of the frames is variable from 60 to 600 bytes and can change based on the environment's channel properties, traffic class, and other parameters as desired. The frames contain a RF preamble, header and trailer flags, TDMA slot markers, a Frame Type indicator, a length field, an optional Frame Check Sequence field, a control field, and an options field that allows us to pass information such as type of FEC, compression, and interleaving factor.

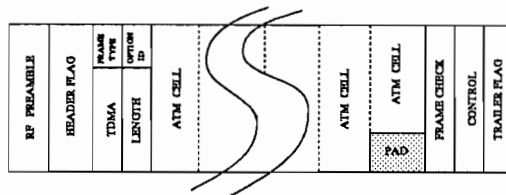


Figure 3. Wireless Data Frame Structure

Figures 4 and 5 show a component level view of a remote node. An edge switch has the same hardware components except that it typically has additional receive cards, one for each remote node in the system, up to a maximum of eight receivers, and a OC-3 fiber ATM card. The host used is a Pentium based PC running a UNIX derivative.

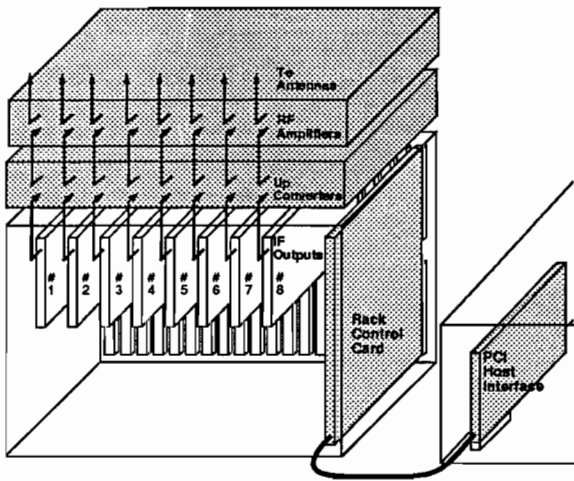


Figure 4. Component Level View

The host interface card is a Peripheral Component Interconnect (PCI) board with a simple interface that runs from the PCI card to a rack mounted system where most of the radio functionality is performed. The host uses the PCI interface to pass packets to the transmitter, read packets from the receiver, update the beam steering tables, and send and receive status and control messages between the host and rack subsystem.

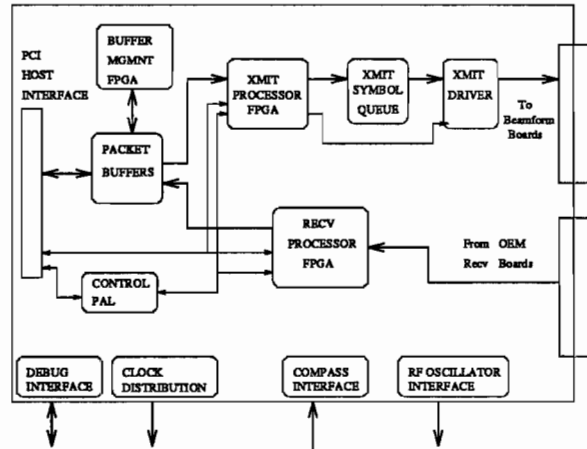


Figure 6. Rack Control Card

The rack control card serves as an interface between the host and various control registers and beamforming memories, and performs the transmission and reception of data. Figure 6 shows a block diagram of the card. The rack control card can be divided into four main components:

- Buffer Management
- Transmit Processing
- Receive Processing
- Support Systems

3.1.1. Buffer Management

The buffer management section manipulates a bank of dual port memories to perform like a set of buffers. As opposed to a more rigid queue structure, this mechanism allows the number and types of beams being used to vary over time. The management FPGA responds to host requests about the space in the buffer, stores frames as they are forwarded from the host, and signals the transmit processor FPGA when there are packets to be processed.

The buffer manager also handles the storage of received words until they are consolidated into complete frames. When an entire frame is assembled, it is DMAed to the main memory location specified by the host. An interrupt is generated when the packet has been transferred, signaling to the host that the new packet has arrived.

3.1.2. Transmit Processing

The Transmit Processing FPGA manipulates the packets before they are sent to the transmitter cards. Packets from each active beam are read from the buffers and "symbolized," i.e. partitioned into symbol-width pieces. As they are symbolized, they are optionally V.35 scrambled, and bit stuffed. The symbols from each beam are then grouped together along with an additional flag for each configured beam which indicates that there is a valid symbol present for that

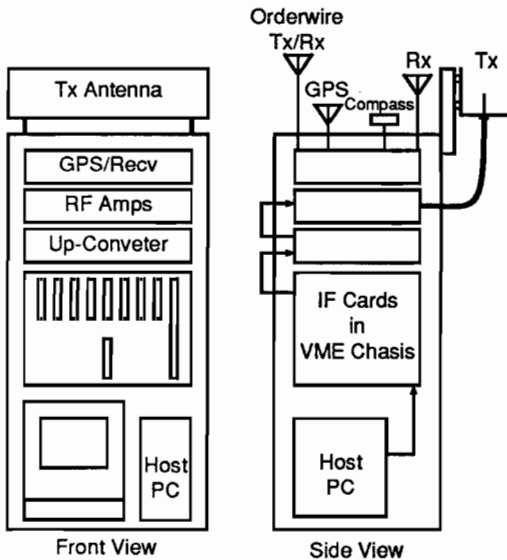


Figure 5. Antenna/Radio Rack

particular beam. This vector of information describing the next block of data to be transmitted is then placed into the transmit buffer from which one vector is read and passed to the beamforming cards each symbol time. A configuration register on the FPGA allows the number and symbol widths of the active beams as well as the data rates of each individual beam to be changed on the fly from the host.

3.1.3. Receive Processing

The receive processing FPGA is designed to interface with multiple receivers. The receivers currently being used are OEM-level boards from Stanford Telecom. The FPGA reads bits from each receive data stream and delineates the frames within them. The FPGA contains a loadable register that holds a TDMA marker value which is used to discriminate which frames are to be kept. As a word is assembled for a given frame it is stored in the buffers as directed by the buffer management FPGA. The receive interface is general and can support both the QPSK and BPSK receivers from Stanford Telecom, as well as custom beamforming receivers intended as future research.

3.1.4. Support Systems

The support systems include a debug interface for programming and debugging the FPGAs, an 80 MHz clock distribution system, an interface to a digital compass to retrieve antenna orientation information, and a register to set the RF local oscillator frequencies for the transmitter and receiver.

3.2. Digital Beamsteering with Spatial Reuse

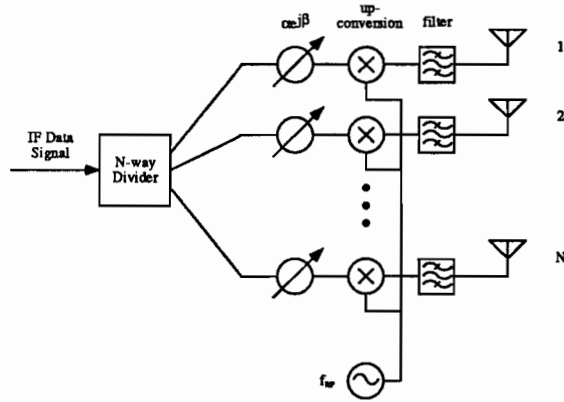


Figure 7. Transmit Steering at RF

Digital beamsteering can be described for a generic modulation scheme as follows [6]. Let the signal samples be represented by the vector

$$s = (s_{-\infty}, \dots, s_{-1}, s_0, \dots, s_t) \quad (1)$$

The most general form of modulation can be expressed as

$$x(t) = \text{Re}[\alpha(s) \exp(j2\pi f_{IF}t + \phi_0 + \Phi(s))] \quad (2)$$

where $\alpha(s)$ represents any form of amplitude modulation, f_{IF} is the IF 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 $\alpha(s_t)$ where t represents the current time index or in phase shift keying, further reduces 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 $\Phi(s_t)$, or even coded modulation schemes like Trellis Coded Modulation. Digital beamsteering introduces an additional relative phase and amplitude of the signal going to each antenna element. Thus, the digitally modulated signal of a single user $x_i(t)$ is modified to

$$x_{ij}(t) = \text{Re}[A_{ij}(t) \exp(j\phi_{ij}(t)) \alpha_i(s_i) \times \exp(j2\pi f_{IF}t + \Phi(s_i))] \quad (3)$$

where subscript i refers to a user index and j refers to a specific element of a phased antenna array. Thus, the composite signal coming to an element is given by

$$X_j(t) = \sum_i \text{Re}[A_{ij}(t) \exp(j\phi_{ij}(t)) \alpha_i(s_i) \times \exp(j2\pi f_{IF}t + \Phi(s_i))] \quad (4)$$

Digitally manipulating the phase of data at RF rates to steer the beam is computationally infeasible and unnecessary. This is due to the fact that relative phase shifts at the intermediate frequency are maintained after up conversion and hence the phase of the data can be adjusted at IF. This can be shown as follows. If an IF waveform $x(t)$ is upconverted to RF we have

$$x(t) = \cos[2\pi f_{IF}t + \phi_{IF}], \quad (5)$$

and

$$X(t) = x(t) \cos[2\pi f_{RF}t], \quad (6)$$

where f_{RF} is the RF carrier frequency. Expanding $X(t)$ and simplifying results in

$$X(t) = \frac{1}{2} (\cos[2\pi(f_{RF} - f_{IF})t - \phi_{IF}] + \cos[2\pi(f_{RF} + f_{IF})t + \phi_{IF}]) \quad (7)$$

$$X(t) = \cos 2\pi[(f_{RF} + f_{IF})t + \phi_{IF}] \quad (8)$$

where it can be seen clearly that the relative phase changes at IF are preserved after the upconversion.

After up conversion the relative phase shifts among all signal paths all the way to the antenna elements must be maintained for the beam steering system to function properly. Exact matching is not necessary if the individual changes are fixed and the system is properly calibrated to adjust for them. Creating and calibrating the phase changes at an intermediate frequency is now a less expensive endeavor.

Numerically Controlled Oscillators (NCOs) can use Digital Signal Processing (DSP) techniques to digitally modulate an internally generated sinusoid with externally provided complex weights. Through proper application of the complex weights any M-PSK or M-QAM modulation technique can be used. However, if changes in the type of modulation take place on a relatively slow basis or are fixed then simplifications are possible. If we assume steering angles and modulation schemes for the beams change on the order of tenths of seconds, then the most rapidly changing component is the data symbols which for our prototype is one to two mega symbols per second per beam. Further simplifications arise if we do not require frequency modulation and constrain ourselves to only amplitude and phase modifications. Under these conditions only a minimum subset of a NCO's capabilities would be used. These constraints therefore allow a simple, cost effective, M-PSK and/or M-QAM modulator and simultaneous phase shifter design that is the basis of our transmitter design.

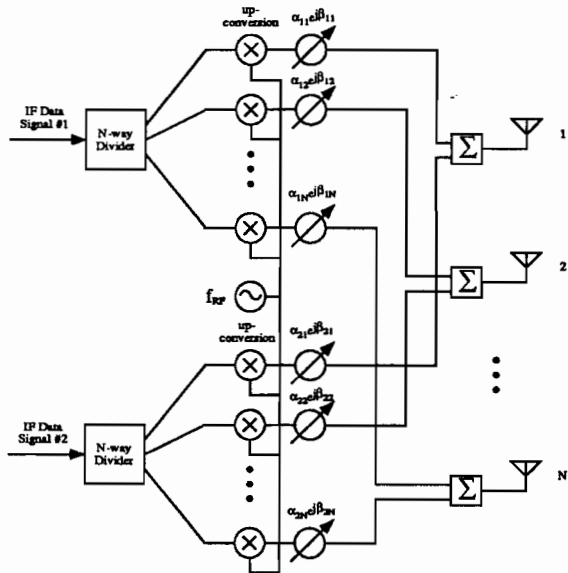


Figure 8. Summing to form multiple beams

The ability to electronically steer beams allows the RDRN system to track moving users and steer the beams to them, however another design goal was to take advantage of spatial reuse. Spatial reuse is the ability to form and steer multiple beams with the same antenna and at the same frequency[7]. Figure 8 depicts a method of forming two simultaneous beams at the same frequency.

Conceptually, the process involves treating each desired beam separately, applying the necessary complex weights on a per antenna element basis and then because the system is linear and superposition holds we can electrically sum the signals for each beam just before each antenna element. The antenna array will form the spatial sum of the individual beam's antenna patterns. This process can be expanded to form many simultaneous beams, within the practical limits of a particular antenna array.

Figure 9 shows a composite antenna pattern for a two user scenario where the positions of the transmitting antenna and remote nodes, Remote Node 1 and Remote Node 2 are all known via GPS, allowing the steering angles for the two beams, Θ_1 and Θ_2 , to be calculated. Additionally, the antenna orientations for each node are known from compass information. For a specific beam with a desired modulation type and steering angle a phase shift can be adjusted for each element such that the waves add constructively at the desired angle. It is also possible to cause the waves to add destructively at angles pointing towards other remote nodes to reduce interference. The quality of the beams is affected by several factors including the number of antenna elements, their topology, and the complex weights associated with each element.

3.2.1. Transmit Beamforming Cards

Several constraints due to the above assumptions are key to the transmitters design. First, the topology of the network is known and the GPS derived locations of the various nodes can be used by a control algorithm to generate the steering angles needed for each of the desired beams. Second, no frequency modulation is used so that all data streams modulate the same frequency IF carrier. This constraint means that regardless of the number of beams, end users, or the complexity of the

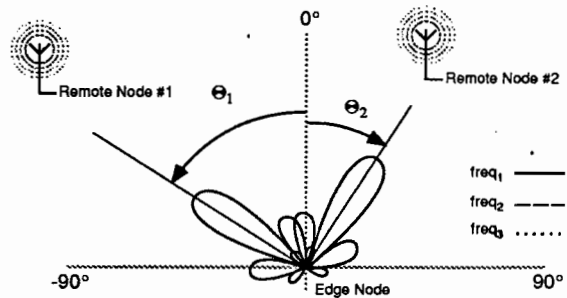


Figure 9. Composite pattern formed by summing

modulation being used, only the amplitude and phase of the composite IF carrier needs to be changed (i.e. the system is linear). Third, the modulation schemes and steering angles change at a rate several orders of magnitude slower than the symbol rate. Finally, the symbol rate is constant across all of the beams being formed.

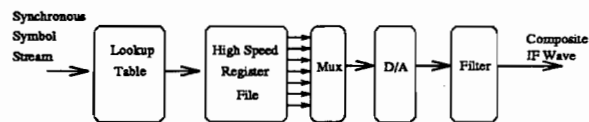


Figure 10. Beamforming Architecture

Figure 10 shows a block diagram of the IF waveform synthesizer that provides the capability to generate a 70 Mhz IF waveform with precise control over its phase and amplitude. The waveform is controlled by a lookup table that contains a representation of the desired IF waveform for each specific combination of symbol data and active data qualifiers. Active data qualifiers for each of the configured beams indicates whether or not there is a valid symbol in the symbol data for each individual beam in this particular symbol interval. The symbol data can represent any valid combination of beams and data for the specific combination of modulation schemes and beams downloaded to the lookup table. The lookup table contains the proper samples required for the D/A converter to generate a sinusoidal waveform of the desired amplitude and phase. The lookup tables and waveform generators are independent for each antenna element, allowing beamforming by varying the relative phase and amplitude for a given lookup vector across the 8 lookup tables. This system design, in addition to the frequency modulation constraint, is not capable of any type of pulse shaping of the output waveform. Finally, the symbol changes among all simultaneous beams are constrained to be synchronous.

The symbol bits can be partitioned and repartitioned into multiple beams each with its own modulation type. The sum of the bits needed per symbol interval, independent of the number of simultaneous beams, is constrained to by our current hardware implementation to be 8 bits. The symbol interval is $1 \mu s$.

3.2.2. The Software Based Radio

By using a software process that can calculate the lookup tables for a desired configuration of beams, their respective steering angles, and their modulation types we are able to have a dynamically reconfigurable software radio[4]. As an example, consider 4 simultaneous beams, with three different modulation schemes as shown below.

Beam	Modulation	Bits/Symbol	Data Rate
1	BPSK	1	1 Mbps
2	QPSK	2	2 Mbps
3	8-PSK	3	3 Mbps
4	QPSK	2	2 Mbps
Totals		8 bits	8 Mbps Total

Determining how a particular edge switch will form its beams is the first step in building the lookup tables. Each edge switch has the capability to produce several electronically steerable wireless links of differing power to establish connections to the users. The problem is to determine:

1. How many beams to form?
2. At which angle to steer these beams?
3. How much power to deliver to each beam?

The current system chooses solutions such that it maximizes the minimum signal-to-interference ratio (SIR) in the set of end users. An iterative algorithm has shown promise in answering these questions. In its current revision, the algorithm has the capability of finding locally optimal solutions to questions (2) and (3) given an answer to question (1). This algorithm takes a number of beams and a set of users around an edge node and calculates the steering angles and relative beam power such that a local maximum in the minimum SIR is achieved. Since an iterative algorithm depends on its starting point, current efforts are focused on finding the starting point that will produce the global solution.

Once the steering angles and relative powers are known, the hardware must be able to deliver the energy to the proper location and with the correct information. If all the information necessary for modulation, calibration, and beam steering is known, the lookup tables can be calculated.

Once the desired phase shift for each element is known for a particular beam, the IF waveform that represents each symbol for that beam is calculated. For a given combination of all symbols across each desired beam the calculated IF waveforms are then summed to form a composite waveform for each particular symbol combination and antenna element. This composite waveform is processed through a set of calibration, normalization, and quantization routines to produce a set of samples, unique for each symbol combination and element, that can be used to produce the desired composite IF waveform. This process is repeated for all permutations of active/inactive data for the currently defined beams. For our example above, the samples are calculated for the case where only beam one is active, for when beams one and three are active and so on. This allows each case to be optimized separately, to minimize interference and to reduce the power used by not transmitting any energy on beams that are idle.

The lookup tables are then filled with every combination of these composite waveforms, for the specific beam scenario chosen. The lookup table will then use the qualifier along with the current symbol table to jump to the correct lookup region each symbol time regardless of whether there is valid data on a particular beam that symbol interval. Each time a steering angle or modulation change is desired the tables must be recalculated and downloaded again.

3.2.3. The RF System

The IF outputs from each of the eight beamform cards must be upconverted in tandem in such a way that the relative phase shifts between each of them are maintained all the way up to the antenna. The input to the upconversion module is the

modulated IF signal produced from the previously described section. It is filtered to attenuate unwanted side lobes and to reject any noise picked up on the run of coaxial cable. The 70 MHz signal is directly input into a double balanced mixer that is driven by one of the eight local oscillators. The resulting RF output signal is fed to the RF power amp stage.

Key to the proper operation of this system is that each of the eight separate RF mixers get a local oscillator signal with identical phase. This is achieved by use of a passive 8-way power divider to distribute the same RF local oscillator to each mixer. The RF LO is a synthesized Phase-Locked oscillator capable of a 900-1600 MHz operating range. The initial prototype works in an Amateur Radio Service (ARS) frequency band from 1240-1300 MHz. The entire system, however, is designed to be capable of operation at up to 2500 MHz with only a few modular RF part changes, namely the RF LO and a single bandpass filter. The next stage is the RF power amplifier subsystem. The input signal to this stage is the output of the RF mixer. This signal is comprised mainly of the sum and difference frequencies produced by the mixer. It also contains LO feed through, in addition to other products and sums. The signal of interest is the sum frequency that falls in the transmission band from 1240-1300 MHz. This signal is filtered out from the others, pre-amplified and fed to the RF power amp. The maximum linear output is 680 mW per amplifier. The final stage before signal reaches the antenna is a back to back pair of directional couplers that form a "dual directional coupler". This series of couplers are used to sample the amplitude, phase, and reflected power in order to calibrate the system.

3.2.4. The Transmit Antenna

The number of antenna elements and their topology or physical arrangement determine the degrees of freedom that are available when generating a specific antenna pattern. The more elements there are to excite, the more beams and nulls that can be controlled.

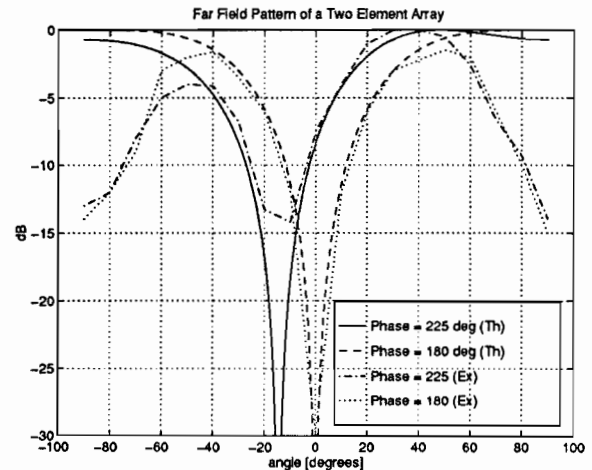


Figure 11. Experimental Two Element Beamforming versus Theoretical

The prototype antenna uses a planar eight element phased array optimized to work at the center of the 23 cm (1240-1300 MHz) ARS band. The array consists of eight quarter wavelength monopoles equally spaced at half wavelengths of the 23 cm operating frequency. The physical dimensions required at this frequency limited the practical number of

elements for a linear array to eight. The rest of the system has been designed to support up to sixteen elements for future tests. A digital compass is mounted on axis with the array to provide the physical orientation of the antenna:

An early experiment driving just two elements in our linear array produced experimental results that matched those predicted by theory. Figure 11 shows antenna patterns recorded for a beam shifted by 180 degrees and then by 225 degrees, overlaid with the patterns for those two cases as produced by the software we use to predict patterns for the beamsteering optimization process.

Work is currently underway investigating cylindrical conformal antenna arrays made of rectangular microstrip patches[3]. The circular geometry will provide 360 degree coverage and a much higher degree of pattern control. Preliminary work has shown that using both amplitude and phase tapers have produced narrower beamwidths and lower side-lobes than either alone, and have shown promise for use in a system that can support more beams in a given cell area.

3.3. Adaptive Software Controlled Radios

The RDRN proof of concept system serves as a testbed for research into adaptive software controlled radios. Considerable work has been spent making a number of the components in the RDRN system configurable from software to support the changing of those parameters in the system when it is deemed useful. There are a number of points in the system where information regarding the operating conditions of the wireless link can be ascertained. One focus of research involves the development of a global process to monitor as many points of information as are available, make an estimation of the current channel conditions, and to adapt the radio parameters to maximize the BER in the current environment.

The parameters that are changeable "on-the-fly" in the system include:

- Modulation type on a per beam basis
- Data rate on a per beam basis
- Data frame size on a per beam basis
- Forward Error Correction Coding
- Interleaving size
- Placement of Beams and Nulls to maximize signal and minimize interference
- Transmit Power

A number of probe points about the system performance include:

- Measured receive signal power level
- Counts of timeouts at the link level
- Counts of corrected data using FEC

A method first proposed in [8] has been adapted to allow for an estimation of the delay profile and noise component of the channel. Our system utilizes Operation and Maintenance (OAM) ATM cells periodically inserted in the middle of the wireless data frames to measure the delay components of the channel. The payload of the OAM cell contains a pseudo random noise sequence that is correlated with the received sequence to generate a delay profile. The estimated delay profile is used to generate an estimate of the received sequence. The estimated receive sequence is then subtracted

from the received signal to provide an estimate of the noise component in the received signal.

Work is currently underway exploring these techniques to allow an adaptive software controlled radio.

3.4. Automatic Network Configuration - Reconfiguration

One important design requirement was to provide a mechanism for automatic network configuration. One application envisioned for the RDRN network would be to quickly provide network infrastructure in disaster relief situations. The ability to rapidly deploy the wireless system is essential to fulfilling our objectives. Automatic reconfiguration responds to the changing topological environment of the wireless system as mobile remote nodes move from one cell to another. The proof of concept system provides a testbed for continuing work into the development of advanced network configuration and management software supporting soft handoffs, fault tolerant links, and further research into mobile ATM issues.

The network configuration research is supported by two components. The first is a 430 Mhz broadcast system based on a 19,200 bps FSK AX.25 packet radio network used as an orderwire for the exchange of link quality reports, physical location information, and port assignments. The second is a software process that utilizes the orderwire to manage all aspects of the wireless links.

3.4.1. Order Wire System

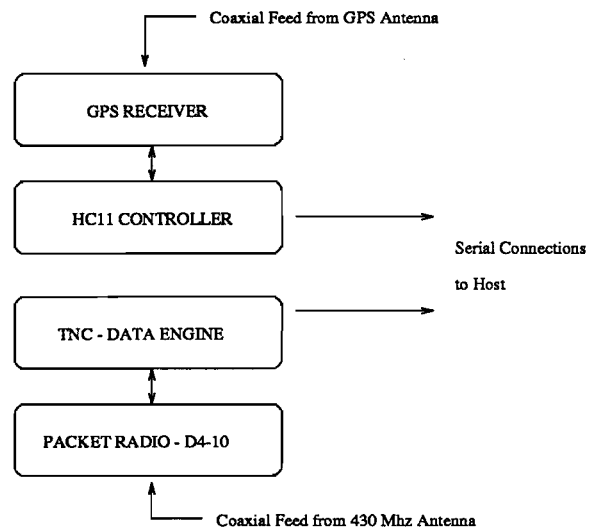


Figure 12. Order Wire System

The orderwire system[2] consists of five modules: a GPS receiver, a HC11 microcontroller, a terminal node controller (TNC), a 430 MHz radio, and a digital compass.

A GPS receiver with a HC11 microcontroller is used to determine the latitude and longitude of each node and the current time. A filter running on a HC11 controller is used to extract the necessary data. The HC11 sorts through the data from the GPS receiver and provides the position and time upon a request from the host. The digital compass can also be polled to provide the current antenna orientation.

3.4.2. Wireless Link Management

Each remote node that becomes active obtains its position from its GPS receiver and then broadcasts that position in a packet on the order wire[1]. This packet is received by

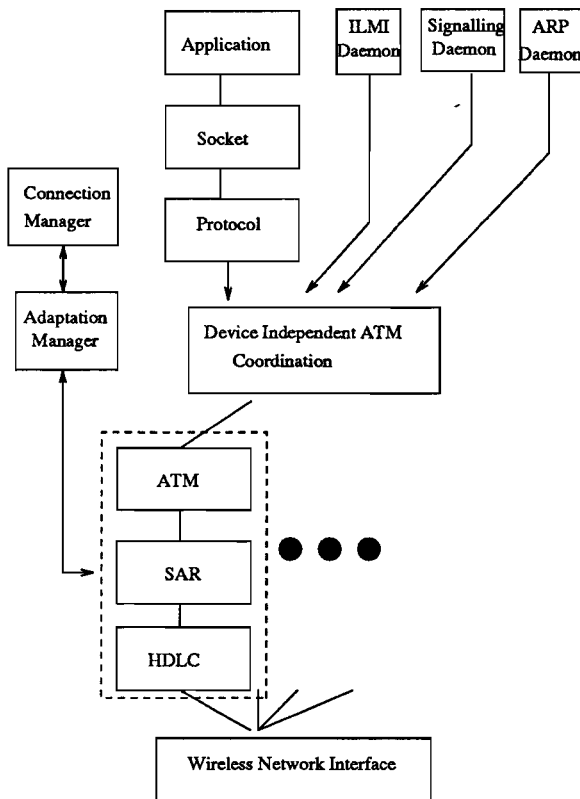


Figure 15. Remote Node Software Architecture

The higher level ATM, protocol, and socket interface modules were drawn from the distribution Linux ATM stack. Also reused from the Linux ATM stack is the ILMI daemon for ATM address registration, the ATMARP daemon, and the signaling daemon used for connection setup and teardown.

3.5.3. Edge Switch Software Architecture

The edge switch uses Q.port code from Bellcore to perform the signaling processing and switch fabric control. The software switch supports switching between the various beams on the same edge switch, and between the wireless and wired ports. Queuing is based on ATM Quality of Service classes. Each wireless connection is referred to as being on a virtual port, and the Edge Switch Adaptation Driver software stack implemented for each virtual port is reused from the remote node. The fiber based OC-3 interface has its own software driver from the standard Linux ATM distribution that is adapted to interface with the switch software.

4. CONCLUSION

The Rapidly Deployable Radio Network is a testbed for research into advanced wireless network systems including protocol design, radio design, antenna design, and system integration. It provides a demonstration of an end-to-end ATM network including wireless links. The network is automatically reconfigurable in response to changes in the environment and resources, allowing rapid deployment.

An advanced radio design is enabled by inexpensive GPS components providing accurate time and position data for all remote users. Multiple independent antenna beams are formed and steered as remote users move, demonstrating the reuse of frequency bands within a wireless cell. Each

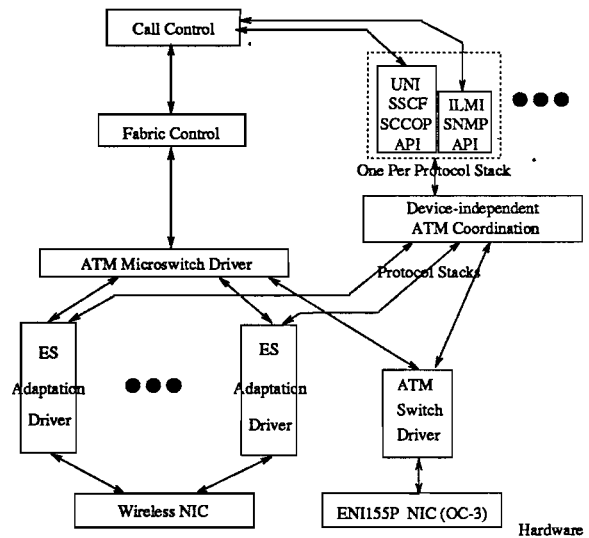


Figure 16. Edge Switch Software Components

of the beams can be adapted to the changing wireless environment by varying modulation, scrambling, power levels, coding schemes, and frame lengths in real time response to link quality updates provided over an out-of-band orderwire network.

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all the "nearby" edge switches. The link management process on each candidate switch then computes the distance between the remote node and all the candidate switches. A first approximation of the best switch to handle the remote node is the physically closest switch. This closest switch's link management process then feeds the new remote node's position information along with the positions of all its other connected remote nodes to a beamsteering algorithm that returns the steering angles for each of the beams on that switch so that all the higher speed links to all of the remote nodes can be established. If a time slot and/or beam is available to accommodate the new remote node, the switch will adjust its beams as needed, record the new links properties in a connection table, recalculate and download the steering information for the transmitter hardware, and send over the orderwire a packet with link setup information indicating to the remote node which switch will be servicing it. If the new remote node cannot be accommodated, the link management process on the switch would send the remote node a packet via the orderwire with the callsign of the next closest switch, to which the remote node could send another position packet. The alternative switch's link management process could then use the beamform algorithm to determine if it could handle the remote node, and so on.

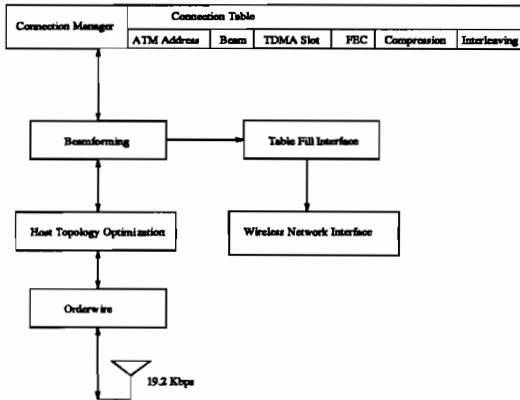


Figure 13. Link Management Process

Once the nodes have been partitioned into beams, and the steering angles for those beams have been optimized, tables must be calculated for the transmitter to allow it to steer the beams to the remote nodes as data is sent. The link management process will calculate the tables and then fill them in on the transmitter so that the radio can begin forming beams.

This scheme uses feedback from the beamforming algorithm together with the position information to configure the network. It should be noted that the underlying AX.25 protocol ensures error free transmissions over the orderwire. If the remote node does not receive a packet within a given time it can use a retry mechanism to ensure successful reception of its position packet.

As the connection table changes over time, when nodes enter or leave the wireless cell, the data protocol stack will build or destroy connection specific portions of the data protocol stack. Each connection has independent protocol stacks to allow for independent HDLC level manipulations on a per connection basis.

3.5. Interface with ATM Infrastructure

The RDRN proof of concept system integrates seamlessly into a traditional ATM network. After the orderwire is used

to establish a high speed radio link - our virtual fiber, a number of processes have to happen to support our integration into an existing ATM network. As soon as the virtual fiber is set up the required signaling virtual circuits are established. An ILMI client on the remote node registers its ATM address with the edge switch node. The edge switch records the virtual port that the ATM address is on for its routing table. The remote node next registers its IP to ATM address with the network ATMARP server. At this point, each remote node has access to the full range of virtual circuits, allowing permanent virtual circuits and switched virtual circuits using Q.2931.

3.5.1. Protocol Architecture

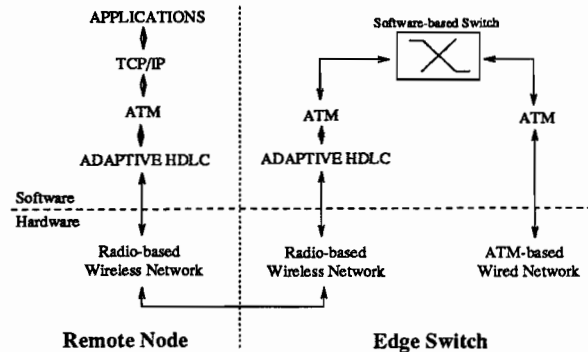


Figure 14. System Network Layers

Figure 14 shows the different network layers that the RDRN system utilizes. The remote nodes communicate through a traditional application layer, support a full TCP/IP suite, perform a classical IP over ATM mapping, then encapsulates packets within an adaptive data link layer before passing them to the network interface driver.

The edge switch has a software based switching fabric, a standard ATM layer, an adaptive data link layer for virtual ports hooked to the wireless network, and network interface card drivers for the wireless and fiber based network ports. Classical IP over ATM is used to support some aspects of our mobility requirements. The ATM addresses assigned to each remote node have topological meaning because they include a switch prefix which indicates which switch they are currently registered with. The remote nodes host IP addresses are used as their "home" network address. It is then possible to manipulate the ATMARP server tables to adjust the IP to ATM address mapping properly when a remote node moves from one edge switch to another so that the IP packets are routed to the correct edge switch as a remote node moves throughout the network.

3.5.2. Remote Node Software Architecture

Figure 15 shows the software architecture for remote nodes in the RDRN system. The link management process oversees the physical link configuration of the wireless network. It responds to orderwire messages to setup the radio so that a physical wireless link can be established. The data protocol stack includes the network interface driver at the lowest level, and an adaptive data link layer which supports our software controlled radio research. A SAR function builds AALS ATM packets before they are passed to the data link layer. The data protocol stack and the link management daemon are interconnected by the adaptation manager which coordinates requests for link level changes over the orderwire with the data protocol stacks to implement those changes.