RDRN:
A Prototype for a Rapidly Deployable Radio Network*

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This paper reports on the initial implementation of an experimental wireless ATM network architecture called RDRN (Rapidly Deployable Radio Network). The RDRN architecture consists of two types of transportable nodes, remote nodes (RNs) and edge nodes (ENs), which utilize GPS-derived location information to rapidly configure themselves into a high capacity wireless network operating at 1-10 Mb/s over distances as far as 10 kilometers. The initial prototype has been deployed and early experiments have been conducted to validate hardware, software, and protocol design and implementation. In addition to describing the RDRN architecture and protocols, this paper details experiences at the DARPA GLOMO '97 demonstration of the RDRN project.

I Introduction

The idea of end-to-end ATM systems extending from wide-area network (WAN) to local-area network (LAN) including a mix of wired and wireless technologies is rapidly gaining momentum. Extensive research has been conducted on desktop ATM technologies area [AB97]. However, the advent of wireless communications and the increase in user demand for efficient wireless services have created new opportunities for ATM technology research. A key question in this effort is how to extend the current LAN/WAN ATM paradigm to support mobile wireless users without impacting the existing ATM infrastructure.

It is critical to enable technologies that support operations in wired/wireless environments. Towards this goal, DARPA initiated the Global Mobile Information Systems (GloMo) program [LRS96] driven by the need to satisfy future requirements such as mobile operation support, rapid deployment, higher speeds, and seamless integration with commercial technology. Over the past two years, the Rapidly Deployable Radio Network (RDRN) project has built and deployed an architecture to satisfy these requirements. More specifically, the RDRN approach addresses the research issues by constructing a system based on the combination of two wireless network technologies; one that enables the rapid deployment of point-to-point wireless links and another that provides seamless support for data communications over established point-to-point links. The joint system, named Rapidly Deployable Radio Network (RDRN), represents a new approach to ATM-based wired/wireless network architectures. This paper describes the design, implementation, and preliminary evaluation of the first prototype of the RDRN architecture.

The rest of this paper is organized as follows. Section II presents the related work in the area. The RDRN architecture is described in Section III. Section IV presents initial performance data obtained from our initial implementation. Our experience during the demonstration of the RDRN project and its interoperability with other mobile research prototypes during GloMo '97 is reported in Section V. Finally, Section VI concludes this paper.

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II Related Work

Extending the ATM paradigm from the wireline to the wireless domain is not a new idea. Several projects have considered and implemented architectures for wireless ATM such as RedNet [C+95], BAHAMA [E+95a], WATMNet [FR95], ORL's RATM [P+96], SWAN [A+96], AWA [U+96], and WAND [Mik96]. Although most of these proposals use similar concepts, they vary in approach and scope. More formal efforts towards the standardization of wireless ATM technology include those of official organizations such as the ATM Forum with their WATM group [Rau97] and the ETSI standard body with their ETSI STC RES 10 project [ETS95], but a standard is far from complete. Our conceptual view provides a different twist to the traditional approach to wireless ATM by combining two different wireless network technologies, an omnidirectional packet radio network and a point-to-point wireless ATM network, with the overall goal being the implementation of a wireless network architecture that is self-configuring and rapidly deployable in an army battlefield situation or a civilian disaster relief operation. By *rapidly deployable* we mean the ability to quickly provide a network infrastructure by way of automated (re)configuration. As mobile nodes move, the topology of the wireless network changes causing point-to-point wireless links (and their associated connections) to be (re)setup or tear-down.

The RDRN design can be best compared to those of BAHAMA [E+95a] and SWAN [A+96] architectures. Like BAHAMA, RDRN features transportable base stations that can connect through high-speed wireless links to support *ad hoc* networking at the backbone level. Similarly, RDRN remote nodes can be interconnected, via access wireless links, over the transportable base stations in an *infrastructure* networking fashion. Unlike BAHAMA, RDRN treats both access and backbone wireless links the same: they are both unreliable links that need support of link-by-link error control mechanisms. While the backbone network in BAHAMA looks closer to a regular ATM network, because the interconnection network is through reliable microwave-based links, it lacks the ease of reconfigurability and rapidly deployment features that characterize the RDRN network at the wireless backbone level. Compared to SWAN, RDRN features a similar base station design: a mobility-aware ATM switch in software which enables wireless user access and wired ATM backbone connectivity. But, unlike SWAN, RDRN also provides wireless ATM backbone connectivity among transportable base stations to support multihop wireless topologies. Earlier reports on RDRN have been published on [B+95][E+95b][SP96][B+97].

The RDRN system is distinguished by the following features:

- architecture composed of two overlaid radio networks [E+95b]

  – low bandwidth orderwire network for network configuration and control

  – high bandwidth wireless ATM network for end-user access to edge nodes and for backbone use among edges nodes

- network configuration, control, and management algorithms based on location information distributed across the orderwire network [B+95][B+97]
- Phased array antenna with digital beamforming and software radio [SP96]
- Mobility-aware software-based ATM switch on edge nodes
- Adaptive wireless communication protocols based on estimated channel conditions

III RDRN Architecture

The main objective of the RDRN architecture is to use an adaptive point-to-point topology to gain the advantages of ATM for wireless networks. Figure 1 shows a high-level view of the RDRN system which is made up of two types of nodes: Remote Nodes (RNs) providing wireless ATM access to end-users and Edge Nodes (ENs) serving as radio access point or base stations to enable switching and connectivity among RN users and the ATM WAN. The architecture is composed of two overlaid radio networks: (1) a low bandwidth, low power, omni-directional network, called *the orderwire network*, intended for location dissemination, topology configuration, and link setup management among RDRN nodes; and (2) a high bandwidth, multi-directional network, called *the WATM network*, that features (a) 1 Mb/s point-to-point connectivity between a RN and an EN and (b) 10 Mb/s point-to-point connectivity among ENs[1]. The radio networks are able to operate over distances as far as 10 kilometers. The orderwire network provides a coarse-grain control mechanism for managing links to be setup over the WATM network while the WATM network provides a fine-grain control mechanism for controlling resources within established links (e.g., ATM virtual circuits) in addition to transporting user data. Unlike traditional wireless architectures, the RDRN system design features two different wireless network technologies in one. The reason for this is twofold: one is that because of its low speed the orderwire offers a high level of *reliability* which is key to the successful establishment and continuous adaptation of the point-to-point links over the not-so-reliable WATM network; the other is *simplicity* in the overall design by utilizing a low bandwidth omnidirectional network for orderwire control operation and a high-bandwidth point-to-point beamforming-based network, which assumes link connectivity, for the WATM network. We note that the architecture presented allows for flexible growth as the demand for rapidly deployable radio networks become more evident.

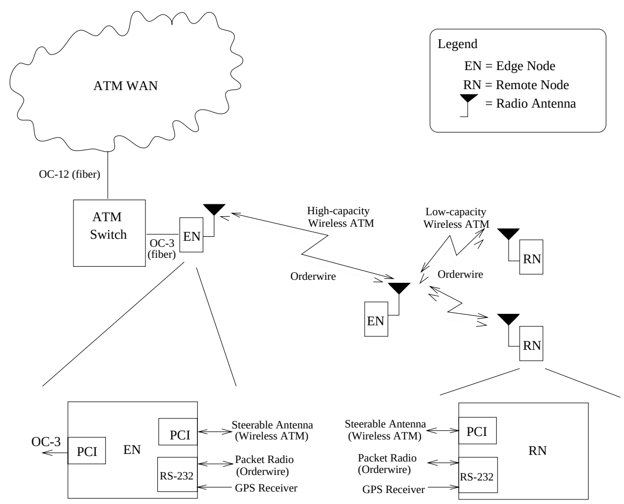

Figure 1: High-level model of the RDRN system

We now proceed to describe the RDRN hardware and software design.

A. RDRN Hardware

Each node in the RDRN system (i.e., RN and EN) is best described as a transportable unit equipped with a laptop computer, a Global Positioning System (GPS) receiver, a 19,200 b/s packet radio transceiver, a custom-designed wireless ATM host adapter PCI card, and a custom-designed phased-array steerable antenna system with digital beamforming. The laptop computer is a Toshiba Tecra 700CT with a 120 Mhz processor attached to a Toshiba docking station with PCI/ISA expansion slots. Both the GPS receiver and the packet radio transceiver are installed on ISA slots while the wireless ATM adapter is installed on a PCI slot. For multimedia support on the RN, the laptop incorporates built-in microphone and speakers for sound, and a video camera is connected to a Matrox Meteor video adapter installed on another PCI slot in the docking station. Optionally, an EN may be equipped with a wired ATM adapter card, which is installed on a PCI slot, if connectivity to a wired ATM network is desired. The

1 The ENs can reside at the edge of a wired ATM network or on their own to create a multihop topology.

antenna system features an omnidirectional receiver, a single-directional (multiple-directional) beamforming transmitter for the RN (EN), and a full-duplex connection to the wireless ATM adapter installed on the laptop. A view of the described RDRN unit built for the first prototype is shown in Figure 2.

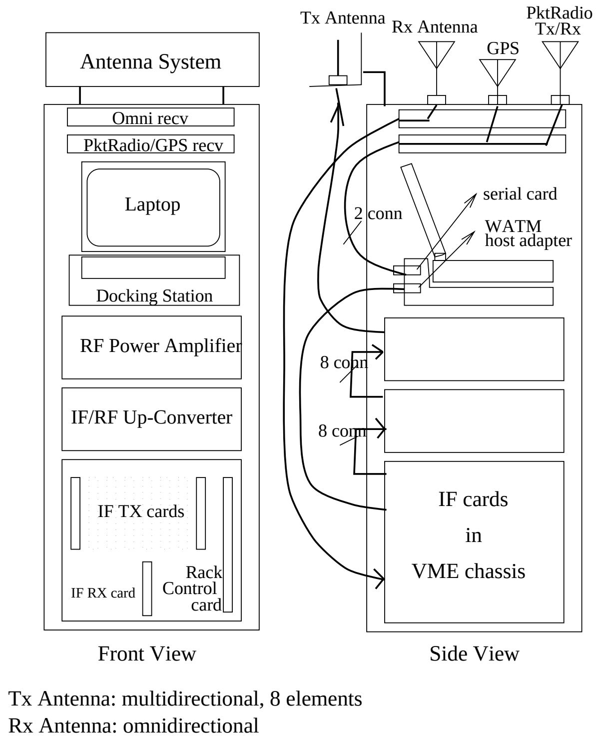

Figure 2: Component View of the RDRN EN/RN unit

When initially deployed, each RDRN node retrieves its location information from the GPS receiver. The location is used by each RDRN node to steer antenna beams towards nearby nodes and nulls towards interferers. An EN is capable of forming multiple digitally formed beams in the direction of other ENs or towards RNs in the vicinity. Multiple digital beams formed by a single transmitter are all of the same frequency to allow spatial frequency reuse. The antenna system is designed to provide 10 Mb/s data rate on beams formed between two ENs and 1 Mb/s data rate on beams formed between an EN and one or more RNs. As many as 64 users (RNs) can arbitrate for the available bandwidth in a particular beam formed by an EN using a TDMA structure; alternatively, a single RN can arbitrate for all of the bandwidth available in such beam. The TDMA mechanism is controlled on the EN by using the GPS time reference to schedule time slots among RNs, within a single beam, that are arbitrating for available bandwidth in the uplink direction. In our initial implementation, digital beamforming is only implemented in the transmit direction while in the receive direction each node communicates back using unique frequencies. Figure 3 shows an overview of the link-level mechanism utilized in the RDRN system.

The Amateur Radio Service (ARS) frequency band from 1240 - 1300 Mhz was chosen for our first system prototype. The bandwidth of each beam is currently constrained to 1 MSymbol/sec. Multiple RNs assigned to an EN are supported through two methods, that is, multiple independent beams of the same frequency can be formed if the RNs are geographically far enough so that there is no interference, or they can be grouped into the same beam using the TDMA mechanism. For further details on the RDRN hardware design the reader is referred to [E+95b] and [SP96]

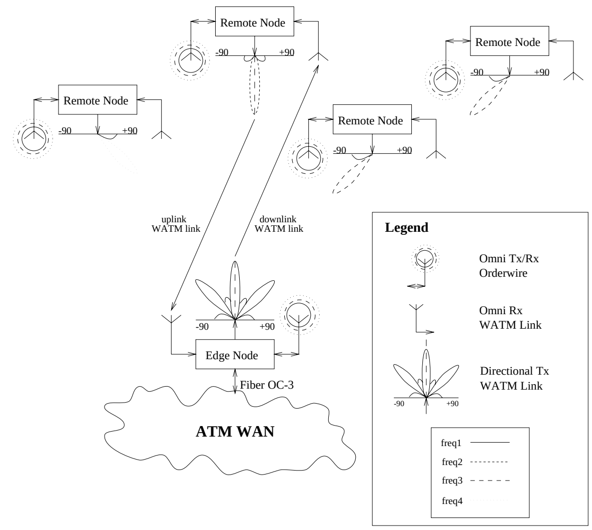

Figure 3: Link-level overview of the RDRN system

B. RDRN Software

Linux has been chosen as the operating environment for the RDRN system running on the laptops. The RDRN software is divided into two major components, the *orderwire modules* and the *WATM modules*, that work in close coordination.

We now proceed to describe the high-level architecture in terms of the algorithm embedded in the RDRN software for both the orderwire network and the WATM network.

1. *The Orderwire Network*

The wireless topology is setup by initially having the ENs broadcast their position over the orderwire network and listen for location broadcast from other RDRN nodes. Similarly, RNs broadcast their position over the orderwire system. A location-based distributed network configuration algorithm is executed to establish WATM link-level connectivity among ENs and sets of RNs or among adjacent ENs. Network reliability is ensured by continuously exchanging location and status information over the orderwire network. As RDRN nodes move, position updates from GPS receivers are used to steer the beams in the correct direction to form point-to-point WATM links. WATM link connectivity is established based on closest physical proximity. The algorithm not only controls the assignment of beam and TDMA slots that requester nodes get assigned to for particular point-to-point WATM links, but also the handoff of users from one EN to another. Topology reconfiguration is thus triggered whenever an EN or RN moves. For instance, when a RN moves, state information is exchanged between the old and new point of entry (i.e., old and new ENs) in order to reroute existing ATM virtual circuits (VCs) established to the RN in question through its new point of attachment. Although the new routing information is exchanged over the orderwire, the actual re(establishment) of VCs is signalled through a lighter mobility-aware version of the NNI signaling protocol. At this stage, handoff support is only provided when a RN moves but we are in the process of revamping the distributed network configuration algorithm to include the interesting case of mobile ENs. This new design will be reported in an upcoming paper. For specific details of the described algorithm and preliminary performance results obtained through simulation the reader is referred to [B+97].

Figure 4 describes the protocol architecture for the orderwire system. Orderwire modules, running as user-level programs on ENs and RNs, receive position updates via a GPS receiver connected to a serial port, and receive and transmit orderwire commands over a protocol based on AX.25 [AX25] via the orderwire connected to another serial port.

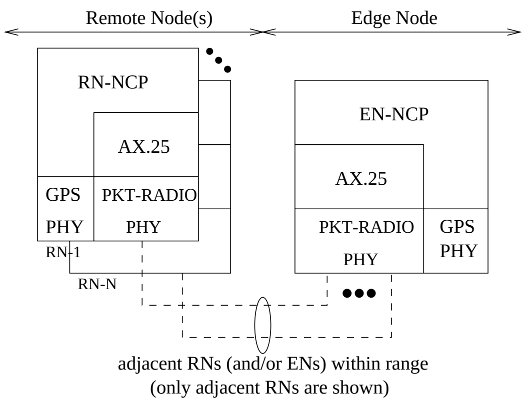

Figure 4: Orderwire Protocol Architecture

Once the RDRN network topology is initialized at the WATM link-level using the orderwire network, the RDRN nodes may start their configuration at the ATM level over the WATM network.

2. *The WATM network*

Unlike all other wireless ATM implementations found in the literature, wireless access in the RDRN network is not restricted to the last hop. This makes the RDRN system very unique by enabling high-speed multihop wireless topologies over long distances [2].

A multihop configuration is possible thanks to the novel design of the RDRN ENs. Basically, an EN can be understood as a traditional base station in wireless system but with expanded functionality to support mobility and virtual ports of different types (wired/wireless). A software-based ATM switch, called *Micro-Switch*, is embedded into the EN's architecture to provide cell-level switching of user data [3]. Given the relative slow speed of wireless links, the realization of ATM switching in software is not a major issue.

Figure 5 describes the protocol architecture for the WATM system. The WATM modules are a mix of user-level programs and kernel drivers embedded into the Linux-ATM software [Alm]. Linux-ATM is used to provide native-mode ATM as well as TCP/IP over ATM support to running applications and user-level signaling programs on both ENs and RNs. On the RN, the WATM protocol stack looks like any other ATM device driver to Linux-ATM. Packet are encapsulated/deencapsulated using AAL-5. Similarly, on the EN, multiple WATM protocol stacks (and a single ATM protocol stack) look like any other ATM device driver to Linux-ATM; however, ATM virtual circuit (VC) packets are routed through the Micro-Switch if configured to use AAL-0 (null) encapsulation, otherwise they are treated as AAL-5 packets and processed accordingly by the Linux-ATM architecture.

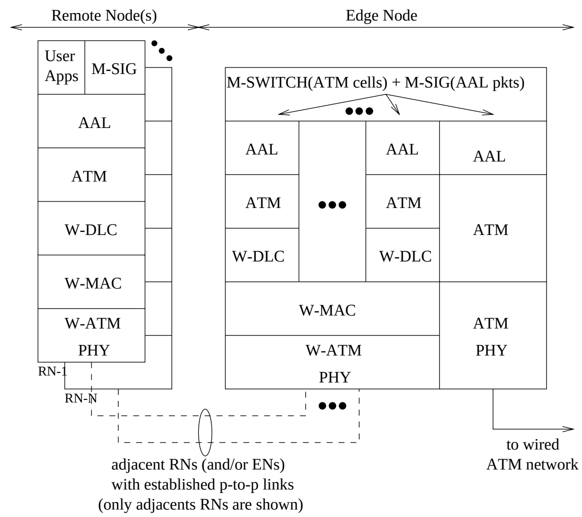

Figure 5: WATM Protocol Architecture

Air packets transmitted over the WATM network are encapsulated using the WATM frame format shown in Figure 6. WATM frames may carry data as encapsulated ATM cells or control information needed to ensure proper link control. There are 3 types of air packets: time-sensitive data packets, guaranteed-delivery data packets, and control packets. Since the WATM frame format derives from the functionality embedded in the WATM stack we proceed to describe the WATM stack in some detail next.

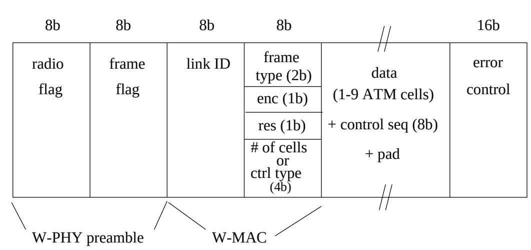

Figure 6: WATM frame format

The WATM stack is composed of several layers: the AAL layer (ATM adaptation layer), the ATM layer (segmentation and reassembly), the W-DLC layer (data link control enhanced for wireless), a W-MAC layer (medium access control for wireless), and a W-PHY layer (physical for wireless). We note that the latter two layers are collapsed into one common layer for multiple WATM stacks on an EN for reasons that will be understood shortly. The AAL layer provides an interface between the WATM stack and the Linux-ATM architecture referred earlier. The ATM layer performs ATM segmentation

[2] High-speed multihop wireless networks configured as wireless backbones are one of many interesting topologies that are enabled by the RDRN architecture; the implications of such scenarios, however, are beyond the scope of this paper.

[3] The incorporation of ATM switching functionality on the base station (EN) itself strongly contrasts with other approaches; our architecture can be fully deployed without the need of a separate ATM switch.

and reassembly functions for AAL-5 and AAL-0 (null) encapsulation types.

The W-DLC layer performs link control operations to transmit a set of ATM cells (the set could include only one ATM cell) over a point-to-point WATM link. The number of ATM cells included on a set is negotiated between peer W-DLC layers and adjusted (adapted) depending on the conditions of the particular WATM link. The idea of putting multiple ATM cells into one WATM frame is to minimize the high effect of encapsulation overhead for a single ATM cell when link quality conditions permits it. We also decided to retain the standard ATM cell structure over the wireless WATM link without modifying the ATM cell header in any way or performing cell header compression but we are considering this type of optimization for future prototype implementations. For packets containing ATM cells, the protocol extends standard ATM QOS over the air by associating the WATM frame type to one of two predefined types of traffic[4]: delay-sensitive (e.g., voice, video) and loss-sensitive (e.g., data), with delay-sensitive traffic having higher priority over loss-sensitive traffic. W-DLC peer layers also negotiate what type of encoding to use for a particular point-to-point WATM link. Experimentation with different encoding schemes and their relation to other adaptive parameters will be object of study in future implementations.

Error detection and retransmissions are also part of the functionality of the W-DLC layer. WATM frames carrying delay-sensitive traffic received with errors are dropped while frames carrying loss-sensitive traffic received with errors are retransmitted. For all traffic types, the wireless channel state is estimated based on the ratio of the number of frames received with and without errors and is assumed to be in either a good state (characterized by a low BER) or a bad state (characterized by a high BER). The WATM frame length (i.e., number of ATM cells in frame) is adapted to the channel state with a larger frame used in the good state and a smaller one in the bad state. For loss sensitive-traffic, an *n-copy* mechanism is also used in the bad state to transmit multiple copies of each frame at a time in order to reduce the total number of retransmission requests. The protocol uses a sliding window and a go-back-N ARQ scheme to guarantee reliability and maximize the throughput under all channel conditions. In addition to performing link control operations over a set of ATM cells, the W-DLC layer also monitors link quality conditions by continuously sending special control packets to its peer W-DLC at the other end. This information is used not only to determine the channel state (i.e., good or bad) to allow adaptation but also to prompt renegotiation of parameters with peer W-DLC layer when the adaptation scheme cannot satisfy the constraint posed by the WATM link.

The W-MAC layer in our system is somewhat simplified since the WATM network already assumes point-to-point WATM link connectivity. The W-MAC header contains a link-level address, frame type (time-sensitive data, loss-sensitive data, or control), encoding scheme (no encoding at the moment), and number of ATM cells (for data type frame) or control type (for control type frames). Three service queues are maintained by the W-MAC layer to prioritize transmission of different frame types. The error control used is a cyclic redundancy check (CRC) computed over the WATM frame payload on this layer and checked at the receiver on the W-DLC layer.

The W-PHY layer appends a header to WATM frame for channel equalization and timing at the physical level on the receiver.

C. System Configuration

Local WATM link configuration strictly follows the orders of a local link manager which works on behalf of the orderwire to setup, adapt, and tear-down WATM point-to-point links. As mentioned before, such point-to-point links have already been established at the physical level by close cooperation between the orderwire and the beamforming antenna system that communicates through the WATM adapter.

Upon establishment of a point-to-point WATM link at the physical level, the link manager activates a WATM stack. By default, one WATM stack is pre-configured in a RN with pre-established well-known VCs setup for ATM control messages (for example, VCI 5 for signaling and VCI 16 for ILMI address registration)[5]. Similarly, multiple WATM stacks are pre-configured in a EN, with the pre-established VCs required for ATM control, and attached to the Micro-Switch on designated virtual ports.

When the link manager, running on any RDRN node, orders the activation of an available WATM stack for use in a point-to-point WATM link, a WATM stack is enabled for data transmission and is assigned an specific link-level address. A link-level address identifies the physical beam and slot that the antenna system is to use when transmitting/receiving to/from a particular point-to-point WATM link. Since a point-to-point WATM link corresponds to either a RN-EN or EN-EN connection, the type of signaling messages that are to be exchanged through such particular link are defined accordingly: User-to-Network Interface (UNI) for RN-EN and Private Network-to-Network Interface (PNNI) for EN-EN connections[6]. Once a WATM stack is enabled at both end of a point-to-point WATM link, it is ready to start transmitting and receiving WATM-encapsulated packets.

The RN ATM address registration occurs after its WATM stack is enabled. By default, the Micro-Switch on each EN is initialized with a unique ATM address prefix. Therefore, ENs assign ATM addresses to link-level connected RNs using the Interim Local Management Interface (ILMI) mechanism. Next, ATM VC connections are established using Classical IP (CLIP) over ATM. In this scheme, an ATM Address Resolution Protocol (ATMARP) server[7] is invoked to resolve a requested IP address into a destination ATM address. The destination ATM address is then used to establish the requested connection using conventional ATM signaling. Finally IP packets can be transmitted and received over established ATM VCs.

[4] For our initial implementation, all ATM cells encapsulated on a WATM frame corresponds to the same ATM VC; therefore, the VC traffic type (i.e., ABR, CBR, VBR, etc) determines what type of WATM frame type to use.

[5] No data is actually transmitted or received until the stack is activated by the link manager.

[6] The Micro-Switch embedded on the EN is able to understand PNNI signaling messages (for connections with other ENs or ATM switch) or UNI signaling messages (for connections with directly connected host or remotely connected –via wireless– RNs) on any of its virtual ports.

[7] Information servers are preferably run on nodes that have direct connectivity to the wired WAN.

IV Preliminary Performance Results

In this section, we present preliminary performance results of experiments conducted to investigate the impact of certain design choices in the RDRN system.

Our first concern was the realization of ATM switching in software (i.e., Micro-Switch) on the EN. In particular, we were interested to determine whether this component may be a bottleneck in our system. Since the Micro-Switch is a self-contained module that can use any ATM-based driver attached to its virtual port, we setup a testbed to connect two host machines through a third machine running as the Micro-Switch. Each host machines consists of a 120 Mhz Pentium PC with one OC-3 ATM host adapter (ENI-155MP) running Linux 2.0.25 with the Linux-ATM distribution. The switching machine consists of a 120 Mhz Pentium PC but with two ENI ATM host adapters operating as two virtual ports. An ATM virtual circuit was configured between the two host through the Micro-Switch. Figure 7 shows the TCP over ATM performance on the receiving machine versus the peak cell rate on the transmitting machine using the *ttcp* tool included in the Linux-ATM distribution. Note that the maximum throughput achieved by the Micro-Switch peaks almost 7.5 Mb/s. Since the WATM links were designed to work up to 1 Mb/s, this is of no concern for EN-RN connections; however, this is a problem for EN-EN connections where 10 Mb/s throughputs are envisioned. Increasing the computing power on an EN will definitely ameliorate this problem for future implementations. The cell latency across the Microswitch module was also measured yielding a 70-120 μsecs delay. We are currently analyzing these limitations so the Micro-Switch component will not longer be a bottleneck for the entire transmission range envisioned on the RDRN system.

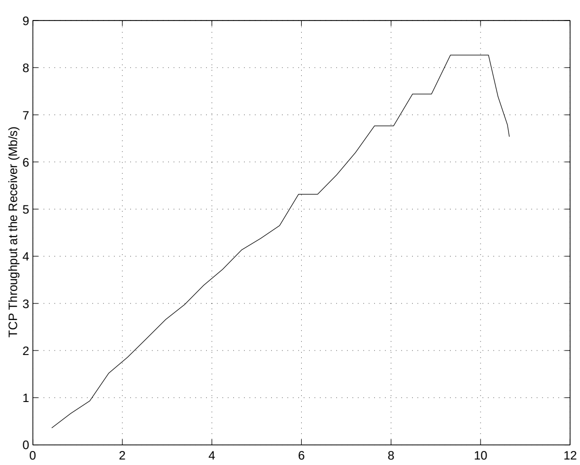

Figure 7: TCP Throughput vs. Transmitted Peak Cell Rate

All remaining experiments described in this section were conducted using the setup shown in Figure 8. A virtual circuit was established between the RN and the fixed node through the EN. The EN and RN were positioned closed enough to minimize the error rate on the wireless channel. Figure 9 shows TCP throughput performance for delay-sensitive traffic. A ramdon error generator was introduced to simulate errors in the channel at specifig bit error rates (BERs). Note that end-to-end TCP throughputs, between the fixed node and the RN, were close to 0.9 Mbps for large WATM frame sizes without errors. However, in the presence of errors, there is an optimal frame size that yields the best throughput in each case. Interestingly, at a high BER (e.g., 10^{-4}), the optimal frame size does not necesarily converge to a single ATM cell size.

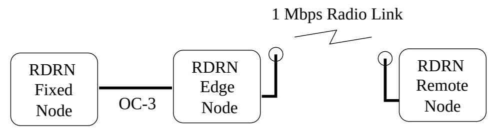

Figure 8: Experimental RDRN Testbed

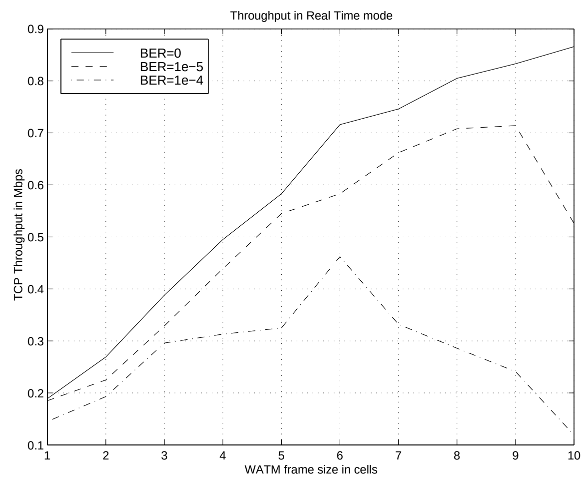

Figure 9: Delay-Sentitive Traffic: TCP Throughput vs. WATM frame size

The effect of WATM frame sizes on round-trip time delays was also measured using the *ping* tool. The experiment was also performed over a delay-sensitive WATM link. The smallest WATM frame size encapsulates only one ATM cell (53 bytes) and yields a constant delay of 6.5 ms; with a delay increase of 3 ms per additional ATM cell transmitted on the WATM frame.

As a final note, we remark the fact that the primary goal of the initial prototype was to provide a proof-of-concept of the architecture and a testbed for the evaluation of new ideas rather than to excel as a high-performance wireless system. For example, we have tested basic beamforming connectivity over long distances (aprox. 10 Kms) but have not yet analyzed the impact of big distances (and observed real error rates) in our design. However, we are currently planning to perform more experiments to better analyze the performance of the RDRN implementation and include optimizations where considered necessary. The analysis and the results of this investigation will be reported in future publications.

V GloMo '97 Demonstration

In July, 1997, an RDRN testbed was demonstrated at the annual DARPA GloMo meeting in Long Branch, New Jersey. The configuration featured an RDRN network prototype in a minimal configuration (i.e., one Edge Node (EN) and one Remote Node (RN)). The demonstration had four goals:

1. demonstrate the orderwire system for network configuration and control,
2. show integration of wired/wireless ATM technologies,
3. demonstrate end-to-end heterogeneous internetworking IP over ATM/WATM, and
4. show interoperability with other GloMo participants and the Internet at large.

Figure 10 illustrates the configuration for the internetworking demonstration. The RDRN testbed has been highlighted for clarity purposes. The first three goals are demonstrated within the context of the RDRN testbed alone. The fourth goal extends the overall testbed to include a connection to the University of California at Santa Cruz (UCSC) Wireless Internet Gateway (WINGs) ad-hoc network and a local Internet Service Provider (ISP) [G^+97].

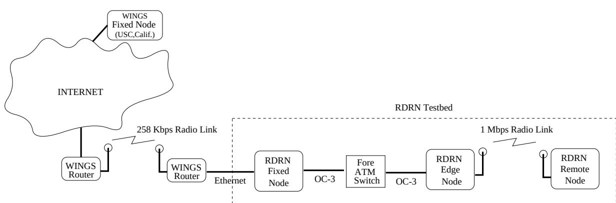

Figure 10: RDRN Internetworking Demonstration

The hardware platform used for the RDRN testbed included four key components:

1. Fixed Node (FN): Desktop Pentium Dell 120 Mhz running Linux 2.0.25 with a PCI Ethernet interface and a PCI Efficient Networks 155 Mb/s ATM interface.
2. ATM Switch: Fore ASX-200wg with 12 OC-3c ports.
3. Edge Switch (ES): Laptop Tecra 700 CT 120 Mhz running Linux 2.0.25 with a PCI Efficient Networks 155 Mb/s ATM interface, a PCI Wireless ATM interface, a serial connection to a GPS receiver, and a serial connection to a 19.2 Kb/s packet radio.
4. Remote Node (RN): Laptop Tecra 700 CT 120 Mhz running Linux 2.0.25 with a PCI Wireless ATM interface, a serial connection to a GPS receiver, and a serial connection to a 19.2 Kb/s packet radio.

Configuration details for each of these demonstrations are provided below.

1. *Orderwire System for Network Configuration and Control*

This exercise demonstrated the orderwire's Network Control Protocol (NCP) in operation between EN and RN. Previously stored GPS time and position information were retrieved from the GPS receivers since the demonstration were performed indoors. The GPS information was then disseminated over the orderwire network to establish a WATM link between the EN and the RN. All relevant information about the NCP protocol was storaged in a Management Information Base (MIB) created for the NCP and retrieved via the Simple Network Management Protocol (SNMP)[Bus]. NCP MIB information, showing the relative connectivity state between the EN and RN, was displayed in a graphical network monitor.

2. *Integration of wired/wireless ATM technologies*

The RDRN testbed featured a wired and wireless ATM segment. The entire segment demonstrated standard ATM interoperability between a fixed node (FN), an ATM switch, an EN running the Micro-Switch, and a RN. End-to-end connectivity was setup between the FN and the RN using ATM virtual circuits as previously indicated in section C. .

3. *End-to-end heterogeneous networking IP over ATM/WATM*

The configuration needed to establish end-to-end communication between the FN and the RN was completed by assigning each node an IP address and configuring their routes to forward to their local ATM/WATM interfaces. Two basic IP-based applications were demonstrated live over the pre-configured VC between the FN and RN: *finger* and *telnet*. A teleconferencing session using the Mbone tools was also configured between the FN and RN. The Mbone session was advertised using the *sdr* (Session Directory Tool) tool, live audio was sent using the VAT Mbone tool, and video stream was sent using the VIC Mbone tool. In particular, the quality of the video transmitted between RN and FN averaged a rate of ten to twelve frames per second.

4. *Interoperability with other GloMo participants and the Internet*

During the GloMo meeting, the RDRN testbed was connected with the UCSC WINGs [G^+97] network. WINGs is a mobile wireless architecture containing packet-radio nodes that are easily reconfigured into wireless IP routers. The wireless IP routers are designed to enable global IP Internet access to ad-hoc networking environments. Just as standard IP routers, WINGs accomplishes its job at the IP level with the addition that it must also adapt to the dynamics of an ad-hoc network in which the nodes move frequently.

Connecting the RDRN testbed to the WINGs network was successful. The WINGs network configuration consisted of a multihop network of WINGs routers. Each WINGs router is basically an IP router (running FreeBSD) with a 10baseT line and a radio interface. The WINGs that was connected to the FN, through an Ethernet hub, served as the border router for the rest of the RDRN testbed.

The overall configuration basically treated the RDRN testbed as a subnet of the major WINGs network. Routing tables were configured in both the WINGs border router and the FN to learn about the existence of each other. Once this was complete, unicast IP packets could be sent from either the FN or RN in the RDRN testbed to any node in the WINGs network and viceversa. Multicast packets could also be sent since the WINGs network acted as a multicast bridge across that domain. Further, since the WINGs network was also connected to a local ISP, connectivity to the Internet at large was available.

In one demonstration, a WWW session was run on the RN for browsing the Internet. In a second demonstration, UCSC was broadcasting an Mbone live video session from Santa Cruz, California via Internet. The sdr Mbone tool running on the RDRN RN detected the UCSC's advertisement and displayed the live video using VIC. As an added bonus, UCSC setup a WWW homepage in which individual users on the RDRN testbed could control the images to be downloaded from the video camera on the UCSC campus. Therefore, by modifying the direction of the camera via WWW, RDRN users could observe different angles of the image displayed by the Mbone VIC tool. Nonetheless, the quality of the video sent averaged a very low rate due to the low channel bit rate featured by the WINGs routers.

VI Conclusions

The RDRN architecture serves as a testbed for research into the area of broadband wireless network systems with an emphasis on rapid-deployment and wireless ATM technology. The first-generation system provided a demonstration of end-to-end ATM, over wired and wireless links and seamless interoperability with legacy IP networks. Preliminary measurements shows 1 Mb/s data throughput available to a remote node located as far as 10 kilometers apart from an edge node and demonstrated the viability and usefulness of adaptive protocol design in response to changes in the environment. Further evaluation demonstrated live video and audio transmissions at reasonable rates (10-12 frames per second for video). Work has begun on the second-generation system of the project to continue evaluating architectural issues and exploring further research opportunities that are enabled by the availability of our testbed.

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