

RDRN: A Rapidly Deployable Radio Network*

– Implementation and Experience –

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To appear on proceedings of ICUPC'98, Florence, Italy, October 1998

Abstract – A proof-of-concept implementation for an experimental wireless ATM network developed within the project RDRN (Rapidly Deployable Radio Network) is presented in this paper. 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 adaptive 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 presents preliminary performance results obtained from the actual implementation.

1 Introduction

The idea of end-to-end ATM systems extending from wide-area networks (WANs) to local-area networks (LANs) including a mix of wired and wireless broadband technologies is rapidly gaining momentum. In order to foster the creation of such a powerful and flexible networking infrastructure, the Rapidly Deployable Radio Network (RDRN) project is investigating wireless ATM technology for high performance, adaptive, rapidly self-configuring mobile radio networks in the framework of the Global Mobile Information Systems (GloMo) [L⁺96] program initiated by DARPA.

The RDRN architecture represents a new approach to ATM-based wired/wireless network architectures. The overall system features the combination of two wireless network technologies: the first, a low-speed packet radio technology to enable reliable out-of-band control for the rapid deployment of point-to-point wireless ATM links; the second, a high-speed beamforming radio technology over which point-to-point wireless ATM links are established. As a result

of our design we envision deployment of highly dynamic topologies requiring end-to-end ATM networking support, seamless interoperability with legacy IP-based networks, and multi-hop operation over wireless nodes that can be apart as far as 10 Kilometers in distance. This paper describes the implementation and initial experience with the first prototype of the RDRN architecture.

The rest of this paper is organized as follows. In Section 2, we present a sampling of related research in the area of wireless ATM architectures. An overview of the RDRN architecture design is presented in Section 3 while the system implementation is described in section 4. Section 5 reports on the preliminary performance results obtained and interoperability experience gathered from our initial implementation. We conclude with a brief discussion in Section 6.

2 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⁺95], 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. 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 wireless network technologies, 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.

The following features distinguish the RDRN system ar-

*This work is partially funded by ARPA contract number J-FBI-94-223 and Sprint under contract CK5007715.

chitecture from those found in the literature:

- * Architecture composed of two overlaid radio networks.
- * Network configuration, control, and management algorithms based on location information distributed across the packet radio network [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 [S⁺98].

3 Overview of the 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) to provide wireless ATM access to end-users and Edge Nodes (ENs) serving as radio access point to enable switching and connectivity among RN users and the ATM LAN. 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 ENs¹. 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.

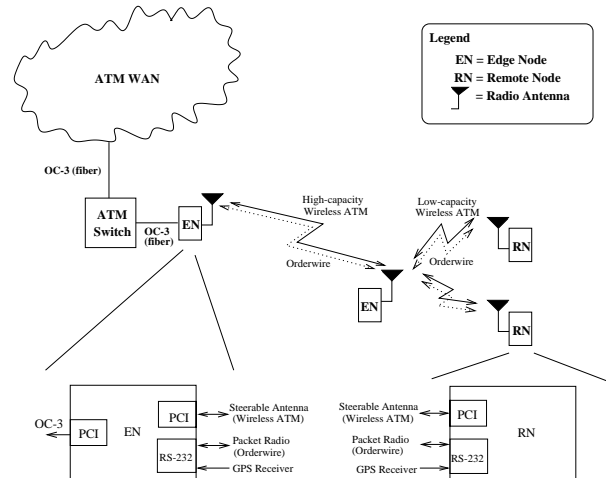


Figure 1: High-level model of the RDRN system

4 RDRN System Implementation

4.1 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. For multimedia support on the RN, the laptop incorporates built-in microphone and speakers for sound, and a video camera for live images. Optionally, an EN may be equipped with a wired ATM adapter card if connectivity to a wired ATM network is desired. The 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.

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 for 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

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

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 2 shows an overview of the link-level mechanism utilized in the RDRN system.

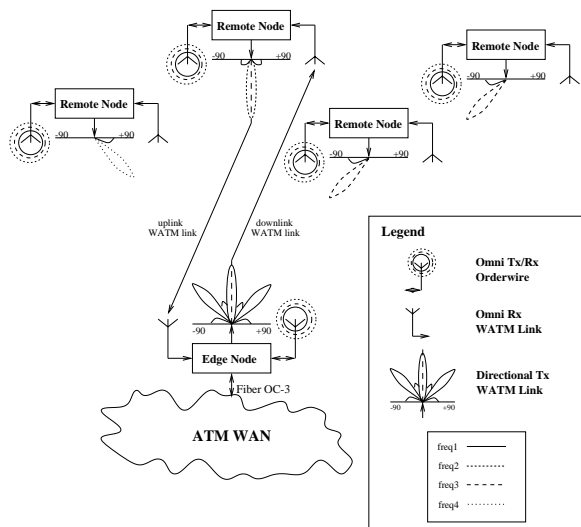


Figure 2: Link-level overview of the RDRN system

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 [SP96].

4.2 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.

4.2.1 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 link-level connectivity among ENs

and sets of RNs or among adjacent ENs. The algorithm not only controls the assignment of node to node link connection but also the assignment of beam to users and the handoff of users from one EN to another. At this stage, handoff support is only provided at the physical WATM link level by the orderwire; however, we are currently studying the implications of such support on the RDRN architecture at large. Survivability 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. Details of the distributed algorithm for control and network management can be found in [B+97].

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. 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. Point-to-point WATM links are established at the physical level by close cooperation between the orderwire and the beamforming antenna system that communicates through the WATM adapter.

4.2.2 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 multi-hop wireless topologies over long distances.

Figure 3 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 (available at <http://lrcwww.epfl.ch/linux-atm>). 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. Similarly, on the EN, multiple WATM protocol stacks (and a single ATM protocol stack) looks like any other ATM device driver to Linux-ATM; however, ATM virtual circuit (VC) packets are routed through the Micro-Switch² if configured to use AAL-0 (null) encapsulation, otherwise, they are treated as AAL-5 packets and processed accordingly by the Linux-ATM architecture.

Air packets transmitted over the WATM network are encapsulated using the WATM frame format shown in Figure 4. There are 3 types of WATM packets: delay-sensitive data packets, loss-sensitive data packets, and control packets. Only data packets are encapsulated using ATM cells.

The WATM stack is composed of several layers: the AAL layer (ATM adaptation layer), the ATM layer (segmentation

²The Micro-Switch is a software-based ATM switch embedded into the EN's architecture to provide cell-level switching of user data

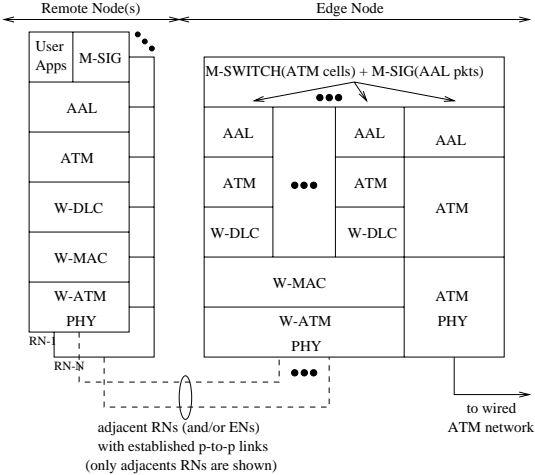


Figure 3: WATM Protocol Architecture

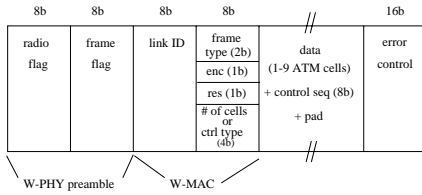


Figure 4: WATM frame format

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). The AAL layer provides an interface between the WATM stack and the Linux-ATM architecture referred earlier. The ATM layer performs ATM segmentation and re-assembly 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 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. Quality of service over-the-air is provided by associating the WATM frame type to one of two predefined types of traffic: high-priority delay-sensitive traffic (e.g., voice, video) and low-priority loss-sensitive traffic (e.g., data). 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 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).

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

5 System Evaluation

5.1 Experimental Results

All experiments were conducted using the setup shown in Figure 5. A virtual circuit was established between the RN and the fixed node through the EN. The EN and RN were positioned close enough to minimize the error rate on the wireless channel. TCP throughputs were measured using a modified *ttcp* tool for ATM VCs. A bit error rate (BER) generator was instrumented on the transmission path of the RN to introduce errors in the wireless channel.

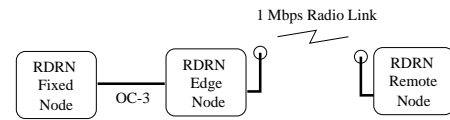


Figure 5: Experimental RDRN Testbed

Figure 6 shows TCP throughput performance for delay-sensitive traffic. For the ideal case (i.e., BER = 0) we achieve throughputs close to 0.9 Mb/s for large WATM frame sizes (> 10 ATM cells). In the good state (i.e., BER = 10e-5) a maximum throughput is achieved at around 0.7 Mb/s for a WATM frame size equivalent to 8-9 ATM cells. On the other hand, in the bad state (i.e., BER = 10e-4) a maximum is reached at 0.45 Mb/s for a WATM frame size equal to 6 ATM cells. One important observation from these results is that there are different optimal points at which air protocols performs the best for various channel conditions (i.e., ideal, good, or bad state). For a more in-depth analysis of the impact of adaptation in our WATM protocol implementation the reader is referred to [S⁺98].

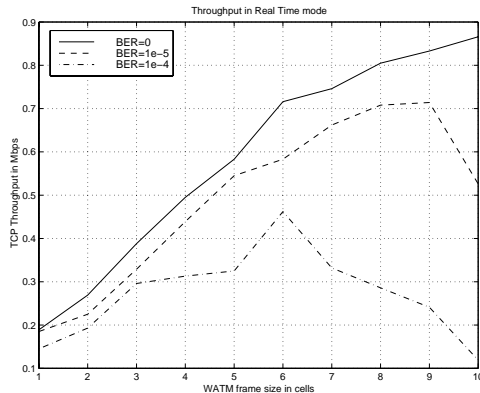


Figure 6: Delay-sensitive Traffic: TCP Throughput vs. WATM frame size

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.

5.1.1 Interoperability Experiences

In terms of interoperability, we have successfully setup a testbed featuring a wired and wireless 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. We have also validated unicast IP operation over a ATM/WATM segment using applications such as *finger*, *ftp* and *telnet*. Multicast IP operation was also demonstrated using the suite of IP teleconferencing tools (i.e., MBONE) such as *sdr* (for session advertisement), *vat* (for audio), and *vic* (for video). We note an average of 10-12 frames per second for live video transmitted between RN and FN (achieving a throughput of up to 128 Kb/s). Finally, we were able to demonstrate end-to-end wireless/wired interoperability with other GloMo participants by connecting the RDRN testbed to the WINGS network [G⁺97] developed at the University of Santa Cruz. We believe this is a major milestone towards achieving RDRN interoperability with a diverse range of heterogeneous wireless technologies.

6 Conclusions

The RDRN architecture serves as a testbed for research into the area of broadband wireless mobile 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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