Wireless Internet Gateways (WINGs) for The Internet

Final Technical Report
Grant No: DAAB07-95-C-D157

October 22, 2001

Prepared for:
Defense Advanced Research Projects Agency/ITO
3701 North Fairfax Drive
Arlington, VA 22203-1714

Submitted by:
The Regents of The University of California, Santa Cruz Campus
1156 High Street
Office of Sponsored Projects
Santa Cruz, CA 95064

Principal Investigator:
J.J. Garcia-Luna-Aceves, Professor
Computer Engineering Department
University of California
1156 High Street, Santa Cruz, CA 95064
e-mail: jj@cse.ucsc.edu

Purpose of Report: This status report is the final contract deliverable summarizing the effort expended by the UCSC team in support of DARPA on Grant DAAB07-95-C-D157.

Contents

1 INTRODUCTION **1**

2 WINGS ARCHITECTURE AND PROTOTYPES **5**
2.1 WING Architecture 5
2.2 Wireless Internetworking Demonstrations 8

3 CHANNEL ACCESS PROTOCOLS **9**
3.1 Collision Avoidance 9
3.2 Group Allocation Multiple Access 10
3.3 Collision Avoidance and Resolution 11
3.4 Dynamic Code Assignment 13

4 LINK-LEVEL SUPPORT OF END-TO-END PROTOCOLS **14**

5 ROUTING PROTOCOLS **15**

1 INTRODUCTION

Today's internetwork technology is oriented toward computer interconnection in relatively stable operational environments, which cannot adequately support many of the emerging civilian and military uses and interconnection of networks. A multihop packet-radio network is an ideal technology to (a) establish an "instant communication infrastructure" in disaster areas resulting from flood, earthquake, hurricane, or fire; and (b) support U.S. military doctrine, which now calls for the ability to communicate soldiers and computers on the move with one another, establish instant communication infrastructures, and extend the global communication infrastructure to the wireless mobile environment.

Achieving multimedia communication on the move and instant information infrastructures presents a challenge, because of the many differences between wireline and wireless networks, the characteristics of portable devices (e.g., power levels, size), and the dynamics of large mobile environments in the battlefield and urban areas.

To meet this challenge, the University of California at Santa Cruz (UCSC) and Rooftop Communications of Mountain View, California, carried out a four-year research project to design, analyze, implement, and test *wireless internet gateways* (**WINGs**) needed to enable the seamless marriage of distributed, dynamic, self-organizing, multihop wireless networks with the emerging multimedia Internet. WINGs enable fundamentally new wireless network architectures in which not all network nodes must have the same capabilities but *any* network node can move with minimal detriment to network performance.

Our approach consisted of advancing the state of the art in the following three areas:

- Innovative packet-radio networking protocols and architectures designed top to bottom to guarantee service for multimedia traffic and to provide a seamless extension of the Internet.
- A unique protocol development environment that provides a seamless transition of new network algorithms and protocols from simulations to the actual embedded radio platform.
- Modular, high-speed, low-cost, commercial, spread-spectrum radio hardware.

WING protocols permit seamless interfacing between a WING-based network and the rest of the global communication infrastructure. The innovative WING protocols developed in this project include channel access protocols, link control protocols, and routing protocols.

Our development and demonstration tools and methodology of WINGs were based on:

- A commercial spread-spectrum radio
- Rooftop's unique protocol development toolkit, called C++ Protocol Toolkit (CPT), which permits the same code used in simulations to be used as embedded software controlling the operation of the transceiver hardware.

The WING prototypes were used and adopted by several other DARPA research groups in the GloMo program, including BBN.

The research work in this project resulted in 25 refereed papers published in journals and conferences, four Ph.D. theses, and two M.S. theses. All of these works are available on line at http://www.soe.ucsc.edu/research/ccrg/publications.html

The theses completed with support from this project are the following:

1. Shree Murthy, "Routing in Packet-Switched Networks Using Path-Finding Algorithms," Ph.D. thesis, Computer Engineering, University of California, Santa Cruz, CA 95064, Sept. 1996. http://www.soe.ucsc.edu/research/ccrg/publications/shree.phd-thesis.pdf

2. Jyoti Raju, "Distributed Assignment of Codes in Multihop Radio Networks," M.S. Thesis, Computer Science, University of California, Santa Cruz, CA 95064, June 1998. http://www.soe.ucsc.edu/research/ccrg/publications/jyoti.masters.pdf

3. Christina Parsa, "Improving TCP Performance over Wireless Networks at the Link Layer," M.S. Thesis, Computer Engineering, University of California, Santa Cruz, June 1998. http://www.soe.ucsc.edu/research/ccrg/publications/chris.masters.pdf

4. Andrew Muir, "Channel Access Protocols based on Transmission Groups," PhD Thesis, Computer Engineering, University of California, Santa Cruz, CA 95064, June 1998. http://www.soe.ucsc.edu/research/ccrg/publications/andrew.phd-thesis.pdf

5. Chane L. Fullmer, "Collision Avoidance Techniques for Packet-Radio Networks," PhD Thesis, Computer Engineering, University of California, Santa Cruz, CA 95064, June 1998. http://www.soe.ucsc.edu/research/ccrg/publications/chane.phd.pdf

6. Rodrigo Garces, "Collision Avoidance and Resolution Multiple Access," PhD Thesis, Computer Engineering, University of California, Santa Cruz, CA 95064, March 1999. http://www.soe.ucsc.edu/research/ccrg/publications/garces.phd.pdf

The technical papers published describing the results of our research in this project are the following:

1. D. Beyer, M.D. Vestrich, and J.J. Garcia-Luna-Aceves, "The Rooftop Community Network: Free, High-Speed Network Access for Communities," *The First One Hundred Feet: New Options for Internet and Broadband Access*, Harvard Information Infrastructure Project, Arlington VA, October 1996.

2. A. Muir and J.J. Garcia-Luna-Aceves, "Group Allocation Multiple Access in Single-Channel Wireless LANs," *Proc. Communication Networks and Distributed Systems Modeling and Simulation Conference*, Phoenix, Arizona, 12–15 January 1997.

3. A. Muir and J.J. Garcia-Luna-Aceves, "Supporting Real-Time Multimedia Traffic in a Wireless LAN," *Proc. SPIE Multimedia Computing and Networking 1997*, San Jose, California, February 1997.

4. R. Garces and J.J. Garcia-Luna-Aceves, "Collision Avoidance and Resolution Multiple Access with Transmission Groups," *Proc. IEEE INFOCOM '97,* Kobe, Japan, April 7–11, 1997. (**Selected for ACM WINET Issue on Best Papers from Infocom 97**)

5. A. Muir and J.J. Garcia-Luna-Aceves, "Group Allocation Multiple Access with Collision Detection," *Proc. IEEE INFOCOM '97*, Kobe, Japan, April 7–11, 1997.

6. S. Murthy and J.J. Garcia-Luna-Aceves, "Loop-Free Internet Routing Using Hierarchical Routing Trees," *Proc. IEEE INFOCOM '97,* Kobe, Japan, April 7–11, 1997.

7. C. Fullmer and J.J. Garcia-Luna-Aceves, "Complete Single-Channel Solutions to Hidden-Terminal Problems," *Proc. IEEE ICC '97,* Montreal, Canada, June 1997.

8. R. Garces and J.J. Garcia-Luna-Aceves, "Collision Avoidance and Resolution Multiple Access: First-Success Protocols," *Proc. IEEE ICC '97,* Montreal, Canada, June 1997.

9. C. Fullmer and J.J. Garcia-Luna-Aceves, "Solutions to Hidden-Terminal Problems in Wireless Networks," *Proc. ACM SIGCOMM '97,* Cannes, France, 14–18 September 1997.

10. J.J. Garcia-Luna-Aceves, C. Fullmer, E. Madruga, D. Beyer, and T. Frivold, "Wireless Internet Gateways (WINGs)," *Proc. IEEE MILCOM '97,* Monterey, California, November 1997.

11. J.J. Garcia-Luna-Aceves and J. Raju, "Distributed Assignment of Codes for Multihop Packet-Radio Networks," *Proc. IEEE MILCOM '97,* Monterey, California, November 1997.

12. R. Garces and J.J. Garcia-Luna-Aceves, "A Near-Optimum Channel Access Protocol Based on Incremental Collision Resolution and Distributed Transmission Queues," *Proc. IEEE INFOCOM '98,* San Francisco, California, March 29–April 2, 1998.

13. A. Muir and J.J. Garcia-Luna-Aceves, "A Channel Access Protocol for Multihop Wireless Networks with Multiple Channels," *Proc. IEEE ICC '98,* Atlanta, Georgia, June 7–11, 1998.

14. J.J. Garcia-Luna-Aceves and C. Fullmer, "Performance of Floor Acquisition Multiple Access in Ad-Hoc Networks," *Proc. IEEE ISCC'98: Third IEEE Symposium on Computers and Communications*, Athens, Greece, June 30–July 2, 1998.

15. R. Garces, J.J. Garcia-Luna-Aceves, and R. Rom, " An Access Etiquette for Very-Wide Wireless Bands," *Proc. IEEE IC3N '98: Seventh International Conference on Computer Communications and Networks*, Lafayette, Louisiana, October 12–15, 1998.

16. A. Muir and J.J. Garcia-Luna-Aceves, "An Efficient Packet-Sensing MAC Protocol for Wireless Networks," *ACM Journal on Mobile Networks and Applications,* Vol. 3, No. 2, pp. 221–234, 1998.

17. R. Garces and J.J. Garcia-Luna-Aceves, "Collision Avoidance and Resolution Multiple Access," *Cluster Computing* (Baltzer Sci. Pub.), Vol. 1, pp. 197–212, 1998.

18. S. Murthy and J.J. Garcia-Luna-Aceves, "A Routing Architecture for Mobile Integrated Services Networks," *ACM Mobile Networks and Applications Journal,* Special Issue on Mobile Networking in The Internet, Vol. 3, No. 4, pp. 391–407, 1998.

19. S. Murthy and J.J. Garcia-Luna-Aceves, "A "A Loop-Free Routing Protocol for Large-Scale Internets Using Distance Vectors," *Computer Communications,* Vol. 21, No. 2, 1998, pp. 147–161.

20. R. Garces and J.J. Garcia-Luna-Aceves, "Collision Avoidance and Resolution Multiple Access with Transmission Queues," *ACM Wireless Networks Journal,* Special Issue on Selected Papers from INFOCOM 97, Vol. 5, No. 2, pp. 95–109, March 1999.

21. C. Parsa and J.J. Garcia-Luna-Aceves, "TULIP: A Link-Level Protocol for Improving TCP over Wireless Links," *Proc. IEEE Wireless Communications and Networking Conference 1999 (WCNC 99)*, New Orleans, Louisiana, September 21–24, 1999.

22. J.J. Garcia-Luna-Aceves and C. Fullmer, "Floor Acquisition Multiple Access (FAMA) in Single-Channel Wireless Networks," *ACM Mobile Networks and Applications Journal,* special issue on Ad-Hoc Networks, Vol. 4, 1999, pp. 157-174.

23. R. Garces and J.J. Garcia-Luna-Aceves, "Collision Avoidance and Resolution Multiple Access for Multichannel Wireless Networks," *Proc. Infocom 2000*, Tel-Aviv, Israel, March 26–30, 2000.

24. R. Garces, J.J. Garcia-Luna-Aceves, and R. Rom, "An Access Etiquette for Very-Wide Wireless Bands," *Computer Communications*, Elsevier, 2000.

25. C. Parsa and J.J. Garcia-Luna-Aceves, "Improving TCP Performance over Wireless Networks at The Link Layer," *ACM Mobile Networks and Applications Journal,* Special Issue on Mobile Data Networks: Advanced Technologies and Services, Vol. 5, No. 1, 2000, pp. 57-71.

The accomplishments in this project involve:

- WING software, prototypes and demonstrations.
- Novel protocols for channel access in multihop packet-radio networks.
- Link-level control techniques to improve the performance of unmodified transport-level protocols across wireless networks.
- Routing protocols for multihop packet-radio networks.

The rest of this report describes key results in each of these areas. Selected papers describing more details on each of these areas, and listed in each section, are included at the end of this report.

2 WINGS ARCHITECTURE AND PROTOTYPES

2.1 WING Architecture

The DARPA packet radio and SURAN programs demonstrated the basic capabilities of ad-hoc networking. However, the ad-hoc networks proposed and implemented in such programs had been designed as opaque subnetworks using an intranet protocol for packet forwarding that enables packets to flow from one packet radio to the other and from one entry point of the ad-hoc network to an exit point. When the ad-hoc network is used as a subnet in an IP internet, one or more of the packet radios connect to the rest of the IP internet through IP routers in order to provide end-to-end connectivity. IP packets are encapsulated in intranet-level packets, and the routing functions within the ad-hoc network are carried out below the IP routing layer.

Internetworking among computers and users over ad-hoc, multihop, wireless communication infrastructures promises to bring the most flexible, robust, and easily deployed and operated networking technology available to today's military and commercial applications. Such *wireless mobile internets* are constructed by a distributed mesh of end-user nodes, sometimes augmented by repeater nodes, which have equal responsibility in the forwarding and automated management of the network. In a wireless mobile internet, there are no dedicated base stations introduce single-point-of-failures in commercial cellular systems. Because a wireless mobile internetwork can be entirely deployed and operated by the end-users, there is no reliance on a wireless service-provider.

The introduction of new nodes to a wireless mobile Internet either extends the coverage and increases the redundancy of the overall network, because each node serves as a repeater when necessary, automatically forwarding data over possibly multiple hops between the source and destination for each stream of data traffic. In addition, the distributed network protocols of a Wireless mobile Internet automatically adapt to changes in the network connectivity caused by mobility or changing environmental conditions. This means, for instance, that mobile end-users who would otherwise find themselves traveling through "coverage holes" of cellular-based systems can often maintain reliable communications in a Wireless Internet due to opportunistic, multihop forwarding by peer nodes.

Finally, by using efficient, service-sensitive, packet-switching protocols, and by conforming to, and when necessary, importing/exporting the open protocol standards of the National Information Infrastructure (currently Internet Protocol version 4 with its companion protocols), these Wireless Internets also promise to form natural, seamless extensions of the wired, multimedia Internet. This Internet compatibility can be accomplished with considerably greater effectiveness than typically possible using commercial, cellular systems due to their historical, circuit-switching orientation.

Wireless mobile internetworking is now enabled by

1. The exploding, widespread use of the Internet, and the accompanying availability of, and familiarity with, a wide array of network applications that facilitate communication and information sharing;

2. Recent development of high-performance, low-cost, and increasingly-miniaturized digital radio and antenna technologies, which have begun to bring these capabilities within the size and cost constraints of individual military and commercial users;

3. The availability of unlicensed, wireless spectrum, enabling the ad-hoc deployment and propagation of high-speed commercial Wireless Internets, with no licensing costs or regulatory delays (thus also facilitating the research and development of Wireless Internets for military applications);

4. The advancement of the wireless internet algorithms and protocols needed to support the rapid, robust, and easy deployment of self-managing, service-sensitive, wireless networks, which also provide seamless connectivity with the wired Internet.

The WINGS project introduced and demonstrated an architecture and protocols for *mobile wireless internetworking*, in which packet-radio nodes are wireless IP routers and the global IP Internet is extended to the mobile wireless environment in a seamless manner. Within the WINGS project, Wireless Internet Gateway (WING) prototypes were built to demonstrate the concept, architecture, and protocols for wireless mobile internetworking. A novel feature of the WINGs is that the same protocol code used to debug and analyze new protocols within a Unix simulation environment is also used to control the operation of the actual WING prototypes.

The WINGS project introduced and demonstrated dramatic improvements in both the core networking technology needed for the realization of Wireless Internets, as well as in the *way* that this technology is developed, fielded, and further advanced. The WINGS project accomplished this by implementing and demonstrating wireless internet gateways (WINGs), and the associated communication protocols, which address many of the goals set forth in the DARPA GloMo project [16]. Specific accomplishments in developing the WING architecture and prototypes included:

- Introducing innovative protocols and architectures for wireless, multihop networks capable of supporting multimedia traffic and providing a seamless extension of the wired Internet. The protocols developed and implemented in the WINGS project doubled the performance achieved during DARPA's "'SURAN" program [3].

- Demonstrating the seamless transition of new protocols from Unix simulations to embedded implementation in prototype WINGs in a matter of days by effectively integrating Rooftop's C++ Protocol Toolkit (CPT) into the research and development process.

- Introducing a modular, object-oriented WINGs Protocol Framework to permit the multi-party development of Wireless Internet protocol stacks by mixing-and-matching protocols developed by the two WINGs contractors (UCSC and Rooftop).

- Leading the development of a Radio API framework and two key APIs that have been adopted as initial standards by the GloMo community towards an open architecture to speed the multi-party development of effective and well-integrated Wireless Internet (and other "packet radio") systems (see [5] and [4]).

- Using these APIs to demonstrate the capability to rapidly prototype a set of WINGs systems using three, different, commercial, high-speed digital radios, with three others (all GloMo-related).

- Participating in a variety of successful demonstrations including small unit operation (SUO) scenarios with interoperability with secure firewalls and information servers, and remote Internet access by interconnecting a multihop WINGs network with the Internet and Hughes' Direct-PC satellite link.

Figure 1 shows a high-level description of the WING software architecture that includes only the main protocols implemented for the WINGs when they operate over a single channel. The key differences between a WING and a traditional router are the following:

- The routing protocol(called WIRP) used is tailored to the multihop wireless domain.

- The routing protocol interacts with the link-layer protocols in order to reduce control traffic needed to maintain routing tables.
- A new set of protocols for link control and channel access (e.g., FAMA, discussed in Section 3) are used to support ad-hoc networks with hidden terminals.

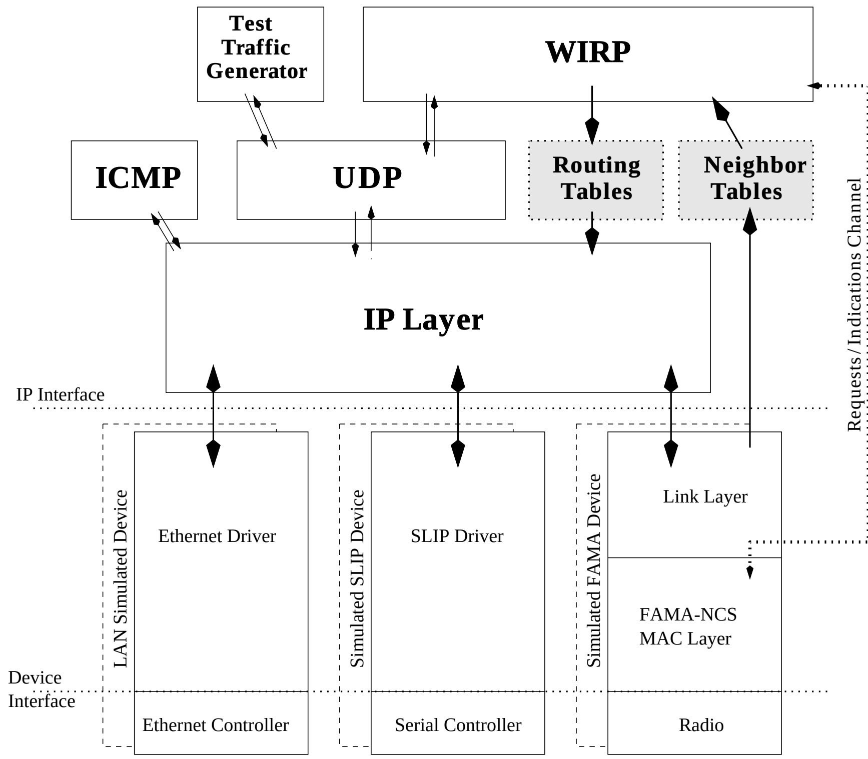

Figure 1: WINGS I Protocol Architecture

An internal traffic generator (TG), which uses the User Datagram Protocol (UDP), is part of the basic architecture and is used extensively in our simulations and testing of WING prototypes.

The Internet Protocol (IP) uses a standard set of interface functions to access the routing table and to obtain routing instructions for packets being forwarded. The interface of IP to the table is the same regardless of what network protocol is used to update the routing table. Similarly, all protocol modules that are connected to the bottom of the IP modules present the same standard IP interface (IpIf) to allow new protocol interface stacks to be easily added or swapped for existing ones.

The WING prototypes supported three interface protocol stacks for interfaces to an Ethernet LAN, a SLIP link, and a digital radio device. The FAMA-NCS protocol and a radio link-layer protocol are used to control the underlying radio device. An Ethernet protocol module which includes the Internet standard Address Resolution Protocol (ARP) is used to control the Ethernet device. A simple SLIP protocol module is used to control the underlying serial communications device. A common device applications programmer interface (API) provides a consistent interface structure between the control protocols and each of these interface devices. This API divides the protocol-to-device interface into three fundamental types of primitives: commands, variables, and signals. In addition, this Device API allows the developer to swap an actual interface device driver for one that simulates the communication channel with no changes required of the interface control protocols. For instance, unbeknownst to the MAC and logical link control protocols, the device driver for the radio used in the WING prototype (the Utilicom LongRanger radio) can be swapped for a module that simulates the radio channel in a simulation environment.

Because of its particular importance for developing open-architecture wireless internetwork systems, special attention was given to the definition of the interface between the protocol software and the digital radio modem. This resulted in the emergence of a pair of standard interface specifications: the *Radio Device API* and the *Physical Radio Interface.* The Radio Device API defines the software interface between the MAC-layer protocols and the "transceiver frame controller" which converts a packet buffers to/from a synchronous bit stream. The Physical Radio Interface defines the lower-layer interface between this transceiver frame controller and the digital radio modem, and consists of a synchronous serial "Data Port" and an abstract "Command Port." The Command Port includes a set of variables, commands, and signals, most of which are also made available to the protocols over the Radio Device API, for controlling and accessing the frequency, RSSI, transmit power, receiver carrier state, and others. The intent of these Radio APIs is to facilitate both collaboration and independent development of the network protocols and digital radio modem hardware which can be easily mixed and matched into well-integrated systems.

The performance of the WING prototypes is described in the following paper:

- J.J. Garcia-Luna-Aceves, C. Fullmer, E. Madruga, D. Beyer, and T. Frivold, "Wireless Internet Gateways (WINGs)," *Proc. IEEE MILCOM '97,* Monterey, California, November 1997.

2.2 Wireless Internetworking Demonstrations

The CPT simulator was incorporated into the WINGs from its inception in November 1995. The baseline protocols were completed and installed on the first embedded system in May, 1996. In July, 1996 a WING ad-hoc network was demonstrated to the GloMo community at the CalNeva Lodge in Lake Tahoe, California. One WING was connected through a SLIP link to a local ISP, and three more were setup though the lodge to form a three-hop network connecting to a laptop running WWW sessions. In a second demonstration a satellite feed from Hughes Research Labs (HRL) was sent over a WaveLan link to a commercial router connected to a WING router and to the laptop via a single-hop WING network.

The WIRP and FAMA protocols were installed and operational on the WINGs in November 1996. In February 1997, these WINGs were demonstrated at the GloMo PI meeting. The network configuration consisted of a hub connected to the UCLA campus network. One WING was connected to the hub and served as the border router for the rest of the WING and their respective clients. Two additional WINGs, each with a FreeBSD client attached to the Ethernet port, were operational in the network. Three internetworking demonstrations were accomplished. A video stream was sent between the two WING clients running FreeBSD and using the VIC Mbone tool over the WING link. Rates of eight to ten frames per second were shown. HRL again provided a satellite video feed as in the Tahoe demonstration, this time to the local subnet. A live video transmission was received and shown also at eight to ten frames per second. The WING router was instantiated in the UCLA routers to the DARTNET connection, and clients on the WING subnet were able to access and download files across DARTNET (i.e, clients were able to connect to SRI International's HTTP server to download files from it).

3 CHANNEL ACCESS PROTOCOLS

The channel access protocols developed in the WINGS project fall into three main categories:

- Collision-avoidance protocols designed to eliminate the collisions of data packets in mutlihop wireless networks using a single or multiple channels.
- Group allocation multiple access protocols designed to provide better support of multimedia applications by establishing and maintaining transmission queues distributedly.
- Collision resolution protocols designed to provide more stable channel access in the context of collision avoidance by resolving the collisions of transmission requests by senders.
- Mechanisms to use multiple channels or codes efficiently in multihop packet-radio networks.

Each class of channel access protocol is described in the rest of this section.

3.1 Collision Avoidance

The hardware characteristics of packet-radios are such that a packet-radio cannot transmit and listen to the same channel simultaneously; therefore, collision detection cannot be used in a single-channel packet-radio network. The throughput of CSMA protocols is very good, as long as the multiple transmitters within range of the same receivers can sense one another's transmissions. Unfortunately, "hidden terminal" problems [21] degrade the performance of CSMA substantially, because carrier sensing cannot prevent collisions in that case.

The busy tone multiple access (BTMA) protocol [21] was the first proposal to combat the hidden-terminal problems of CSMA. BTMA is designed for station-based networks and divides the channel into a message channel and the busy-tone channel. The base station transmits a busy-tone signal on the busy-tone channel as long as it senses carrier on the data channel. Because the base station is in line of sight of all terminals, each terminal can sense the busy-tone channel to determine the state of the data channel. The limitations of BTMA are the use a separate channel to convey the state of the data channel, the need for the receiver to transmit the busy tone while detecting carrier in the data channel, and the difficulty of detecting the busy-tone signal in a narrow-band channel.

One of the first protocols for wireless networks based on a handshake between sender and receiver was the SRMA (split-channel reservation multiple access) [22]. According to SRMA, the sender of a packet uses ALOHA or CSMA to decide when to send a request-to-send (RTS) to the receiver. In turn, the receiver responds with a clear-to-send (CTS) if it receives the RTS correctly; the RTS tells the sender when to transmit its data packet. Although SRMA was proposed with one or two control channel for the RTS/CTS exchange, the same scheme applies for a single channel.

Since the time SRMA was first proposed, several other medium access control (MAC) protocols have been proposed for either single-channel wireless networks or wireline local area networks that are based on similar RTS-CTS exchanges, or based on RTSs followed by pauses [2, 9, 17]. Karn [13] proposed a protocol called MACA (multiple access collision avoidance) to address the problems of hidden terminals in single-channel networks. MACA amounts to a single-channel SRMA using ALOHA for the transmission of RTSs; it attempts to detect collisions at the receiver by mans of the RTS-CTS exchange without carrier sensing. The IEEE 802.11 committee proposed a MAC protocol for wireless LANs that includes a transmission mode based on an RTS-CTS handshake (DFWMAC [8, 12]).

In this project, we developed a new variation on MAC protocols based on RTS-CTS exchanges called FAMA-NCS (floor acquisition multiple access with non-persistent carrier sensing). The objective of FAMA-NCS is for a station that has data to send to acquire control of the channel in the vicinity of the receiver (which we call "the floor") before sending any data packet, and to ensure that no data packet collides with any other packet at the receiver. Sufficient conditions were verified for FAMA protocols to completely eliminate hidden terminal problems in multihop wireless networks. FAMA protocols achieve a maximum throughput of 30% of channel capacity with hidden terminals, which is more than twice the expected performance of CSMA with acknowledgments and hidden terminals.

In addition, a multi-channel FAMA protocol, FAMA-MC, was designed to take advantage of the availability of multiple frequency channels or transmission codes. FAMA-MC was analyzed for the case of a fully-connected network. In the case in which each network node can be assigned its own channel, the maximum throughput achievable in FAMA-MC was shown to be 0.45 for any given node, which is very close to the maximum achievable throughput of 0.5 for any node. The following paper, which is included at the end of this report, describes FAMA and its performance in networks with hidden terminals:

- J.J. Garcia-Luna-Aceves and C. Fullmer, "Floor Acquisition Multiple Access (FAMA) in Single-Channel Wireless Networks," *ACM Mobile Networks and Applications Journal,* special issue on Ad-Hoc Networks, Vol. 4, 1999, pp. 157-174.

3.2 Group Allocation Multiple Access

Several approaches have been proposed in the past to combine contention schemes with reservations, token-passing, or polling (e.g., [12]). However, relatively few proposals have been reported for fully distributed single-channel packet-radio networks that attempt to provide performance guarantees without polling or time slotting.

In this project, we developed a novel channel access protocol for single-hop packet-radio networks that we call the *Group Allocation Multiple Access* protocol (GAMA). GAMA provides dynamic reservations of the channel and its implementation complexity is comparable with that of CSMA protocols. GAMA builds a dynamically-sized "cycle" that grows and shrinks depending upon traffic demand. Each cycle consists of a contention period of up to a maximum duration and a group-transmission period during which one or more stations transmit data packets without collisions. GAMA places a limit on the length of the group-transmission period, which allows GAMA to bound the interval between occurrences of a transmission period. A station with data to transmit requests to join the transmission group by transmitting an RTS (Request To Send) packet. The RTS packet contains the minimum and optimum bandwidth required to transmit the message. If there is enough space available in the cycle, t he station is allowed to use the optimum amount of bandwidth. Otherwise, the station may use any bandwidth which is available; if the remaining bandwidth is less than the minimum amount requested, the station will back-off. Once a station has been added to the transmission group, it is able to up to use its alloted bandwidth each cycle. A position in the transmission group is allocated to an individual station, and a station can continue to transmit in this position as long as it has data to send. GAMA ensures that there are no collisions of data packets, and that once a station has reserved a position in the group-transmission period, it will be able to transmit

GAMA combines the best features of CSMA and contention-free protocols like TDMA or dynamic reservations. On the one hand, like CSMA, GAMA is very efficient under light load. On the other hand, GAMA is much more stable under heavy loads than CSMA, because it permits stations in the transmission group to send packets independently of new requests for additions to the transmission group.

We extended GAMA to operate without the need for carrier sensing. The resulting protocol GAMA-NPS (for non-persistent packet sensing) is the first single-channel multiple access protocol to outperform CSMA without using carrier sensing. GAMA-NPS guarantees minimum traffic rates in a wireless network for real-time multimedia applications. GAMA-NPS is being extended to operate in a multihop packet-radio network. GAMA-NPS will provide much higher throughput than can be achieved by contention-based MAC protocols, without the cost and complexity associated with TDMA schemes.

In addition, we extended GAMA to operate in multihop networks. The resulting protocol is called GAMMA (group allocation multihop multiple access) and uses one channel per receiver to avoid interference. GAMMA is stable under high loads and achieves a maximum throughout that is very close to the maximum possible throughput of 0.5 per node. GAMMA builds collision-free transmission schedules for each node using a handshake between sender and receiver. It relies on the synchronization of nodes, such that nodes know when an intended receiver can receive requests for additions to its collision-free transmission schedule.

The following papers, which are included at the end of this report, describe key aspects of our work on GAMA protocols:

- A. Muir and J.J. Garcia-Luna-Aceves, "An Efficient Packet-Sensing MAC Protocol for Wireless Networks," *ACM Journal on Mobile Networks and Applications,* Vol. 3, No. 2, pp. 221–234, 1998.
- A. Muir and J.J. Garcia-Luna-Aceves, "A Channel Access Protocol for Multihop Wireless Networks with Multiple Channels," *Proc. IEEE ICC '98,* Atlanta, Georgia, June 7–11, 1998.

3.3 Collision Avoidance and Resolution

Many of the medium access control (MAC) protocols for wireless LANs proposed to date are based on a collision avoidance dialogue between senders and receivers [2, 13]. A sender sends a request-to-send (RTS) to the receiver, who in turn sends a clear-to-send (CTS) if it receives the RTS free of errors; only then can the sender transmit a data packet. These protocols solve collisions by backing off and rescheduling RTS transmissions. As with CSMA protocols, this procedure yields good results if the RTS traffic is low, but is inherently unstable. As the RTS transmission rate increases, the constant RTS collisions can cause the channel to collapse, bringing the flow of data packets to a halt when no new data transmission queues can be started. A way to stabilize the system is by increasing the retransmission delays.

Several stable MAC protocols have been proposed in the past based on tree-splitting algorithms (e.g., [7, 10, 18]). Those protocols in which data packets are used to resolve collisions achieve throughput below 0.6 [24]. More recent MAC protocols have been proposed that implement collision resolution using either control packets that are much smaller than data packets, or are based on the ability of the transmitted to abort transmission rapidly after detecting collision (e.g., [6, 11, 19]). Among those stable MAC protocols that achieve high throughput, some build a separate queue for the transmission of data packets, in addition to the stack or queue of the control packets used for collision resolution. However, prior protocols based on data transmission queues and collision resolution require the establishment of time slots or mini-slots for the transmission of control packets [25, 23].

In this project, we developed the collision avoidance and resolution multiple access (CARMA) protocol with transmission queues to provide collision-free data transmission and stable resolution of requests by stations that are added to transmission queues. This work was reported in the paper "Collision Avoidance and Resolution Multiple Access with Transmission Groups," by R. Garces and J.J. Garcia-Luna-Aceves, which was selected for a special issue of the WINET Journal on best papers from the Infocom 97 conference.

We also developed the incremental collision resolution multiple access (ICRMA) protocol that, in contrast to prior MAC protocols based on distributed queues, does not require time slotting to operate. ICRMA builds a distributed transmission queue dynamically using a deterministic tree-splitting algorithm. A station attempts to join the transmission queue during contention intervals by sending an RTS to any intended receiver, who sends a CTS if the station can join the queue. RTSs are sent according to a deterministic tree-splitting algorithm that resolves all the requests for the queue that arrive during the same contention interval. Access time to the channel is divided into rounds of transmissions for all members of the transmission queue, which we call a queue-transmission period, followed by short contention periods during which stations attempt to join the queue. The queue-transmission period is a variable-length train of packets from stations that have been added to the transmission queue by successfully completing a collision-resolution round in a previous contention period. A single round of collision resolution (i.e., a success, and idle or a collision of control packets) is allowed in each contention period. The control packets used in each contention period are much smaller than data packets.

ICRMA is more attractive than previous dynamic reservation schemes for wireless (and wired) LANs in that it does not require time synchronization or the definition of control frames of fixed duration over which the slots for the data frame can be reserved. It is also more attractive than token passing schemes in that no fixed schedule exists for passing the token. ICRMA was shown through analysis and simulation to achieve a maximum throughput within 5% of the maximum achievable throughput by an ideal protocol.

The collision-resolution schemes developed for CARMA and ICRMA were applied to the development of an etiquette of channel re-use to share and access very wide wireless frequency bands. The following papers, which are included at the end of this report, describe key aspects of our work on CARMA protocols:

- R. Garces and J.J. Garcia-Luna-Aceves, "Collision Avoidance and Resolution Multiple Access," *Cluster Computing* (Baltzer Sci. Pub.), Vol. 1, pp. 197–212, 1998.
- R. Garces and J.J. Garcia-Luna-Aceves, "Collision Avoidance and Resolution Multiple Access with Transmission Queues," *ACM Wireless Networks Journal,* Special Issue on Selected Papers from INFOCOM 97, Vol. 5, No. 2, pp. 95–109, March 1999.
- R. Garces and J.J. Garcia-Luna-Aceves, "Collision Avoidance and Resolution Multiple Access for Multichannel Wireless Networks," *Proc. Infocom 2000*, Tel-Aviv, Israel, March 26–30, 2000.
- R. Garces, J.J. Garcia-Luna-Aceves, and R. Rom, " An Access Etiquette for Very-Wide Wireless Bands," *Proc. IEEE IC3N '98: Seventh International Conference on Computer Communications and Networks*, Lafayette, Louisiana, October 12–15, 1998.

3.4 Dynamic Code Assignment

Using code division multiple access (*CDMA*) in packet-radio networks permits multiple stations within range of the same receivers to transmit concurrently, without interference. Several multiaccess protocols have been proposed and commercial systems have been deployed that take advantage of CDMA. An important design consideration in a multihop packet-radio network using CDMA is the assignment of transmission codes to network nodes. In a large network, the number of transmission codes is smaller than the number of nodes, and senders and receivers must agree on which transmission code to use in a way that avoids interference as much as possible.

We designed and analyzed a distributed algorithm for assigning codes in a dynamic, multihop wireless radio network. The algorithm does not require any form of synchronization and is completely distributed. The algorithm can be used for both the transmitter oriented and receiver oriented code assignment. The algorithm is proven to be correct and its complexity is analyzed. The implementation of the code assignment algorithm as part of the medium access control (MAC) and routing protocols of a multihop packet-radio network is discussed.

The algorithm and its advantages are described in the following paper:

- J.J. Garcia-Luna-Aceves and J. Raju, "Distributed Assignment of Codes for Multihop Packet-Radio Networks," *Proc. IEEE MILCOM '97,* Monterey, California, November 1997.

4 LINK-LEVEL SUPPORT OF END-TO-END PROTOCOLS

Supporting multimedia applications over wireless networks requires such end-to-end protocols as TCP to operate efficiently. Unfortunately, bursty errors in wireless channels reduce TCP's throughput dramatically, because TCP interprets packet losses as a sign of congestion, which forces TCP to reduce its "congestion window" and enter a congestion avoidance phase during which the congestion window is incremented by one segment every round-trip time. Considerable work has been reported on ways to improve th e performance of end-to-end protocols over wireless networks and links, specially TCP's performance. However, prior work has focused on modifications to the transport protocols and solutions at the network level that require maintaining state of the end-to-end connections flowing through some nodes [1].

In this project. we designed, verified, and analyzed the transport unaware link improvement protocol (TULIP), which dramatically improves the performance of TCP over lossy wireless links, without competing with or modifying the transport- or network-layer protocols.

TULIP is tailored for the half-duplex radio links available with today's commercial radios and provides a MAC acceleration feature to improve throughput. TULIP's timers rely on a maximum propagation delay over the link, rather than performing a round-trip time estimate of the channel delay.

TULIP does not require a base station and keeps no TCP state. TULIP is exceptionally robust when bit error rates are high; it maintains high goodput, i.e., only those packets which are in fact dropped on the wireless link are retransmitted and then only when necessary. The performance of TULIP was compared against the performance of the Snoop protocol (a TCP-aware approach) [1] and TCP without link-level support. The results of simulation experiments using the actual code of the Snoop protocol show that TULIP achieves higher throughput, lower packet delay, and smaller delay variance.

TULIP is described in detail in the following paper, which is included at the end of this report:

1. C. Parsa and J.J. Garcia-Luna-Aceves, "Improving TCP Performance over Wireless Networks at The Link Layer," *ACM Mobile Networks and Applications Journal,* Special Issue on Mobile Data Networks: Advanced Technologies and Services, Vol. 5, No. 1, 2000, pp. 57-71.

5 ROUTING PROTOCOLS

There have been several proposals for hierarchical routing, which vary in the way in which the nodes are organized (addressing scheme) and the routing algorithms used. With very few exceptions, prior proposals for hierarchical routing have assumed variants of the Distributed Bellman Ford algorithm or topology-broadcast algorithms. In the backbone scheme for hierarchical routing used in OSPF, a network is divided into areas connected by a backbone. A number of algorithms have been proposed that eliminate the counting-to-infinity problem of DBF and eliminate loops altogether. These algorithms are based on the maintenance and incremental exchange of shortest-path routing trees by routers. They can be viewed as distributed implementations of Dijkstra's shortest path algorithm, while link-state algorithms require a router to have a topology map over which it runs Dijkstra's algorithm. A few of these shortest-path-tree-based algorithms have been shown to outperform link-state algorithms. However, because they rely on each router knowing the shortest path tree to every destination, they force a router to know more "host routes" (corresponding to individual routers) than would be necessary if DBF were used. Furthermore, in the Internet, routing information for individual remote routers may not be available because of subnetting and masking.

We designed, verified, and analyzed the performance of the first hierarchical routing algorithm based on the maintenance and exchange of hierarchical routing trees. We call this algorithm the *Hierarchical Information Path-based Routing* (HIPR) algorithm. Its main idea consists of providing a distributed implementation of Dijkstra's shortest path algorithm running over a hierarchical graph organized in areas according to McQuillan's scheme for hierarchical routing. The path-finding algorithms developed by Murthy and Garcia-Luna-Aceves (e.g., see [20]) were extended for this purpose. The following paper describes HIPR in detail:

- S. Murthy and J.J. Garcia-Luna-Aceves, "Loop-Free Internet Routing Using Hierarchical Routing Trees," *Proc. IEEE INFOCOM '97,* Kobe, Japan, April 7–11, 1997.

In addition to our theoretical work, we implemented the wireless internet routing protocol (WIRP) in CPT. WIRP was based on the algorithm described in [20], and was one of the most efficient routing protocol for ad-hoc wireless networks reported at the time of its design. WIRP is completely distributed and scalable, and converges as fast as protocols based on flooding of topology maps without incurring the same large traffic overhead. WIRP runs on top of UDP and supports IP address masks, just like RIPv2. WIRP has been integrated with FAMA protocols to minimize control traffic. Simulation studies confirm that the routing algorithm on which WIRP is based requires orders of magnitude fewer operations to update routing tables than OSPF, incurs no routing-table loops, and requires far less control traffic than protocols representative of the state of the art.

References

[1] H. Balakrishnan et al, "A Comparison of Mechanisms for Improving TCP Performance over Wireless Links," *IEEE Trans. Networking*, Vol. 6, No. 5, Dec. 1997.

[2] V. Bharghavan, A. Demers, S. Shenker, and L. Zhang, "MACAW: A Media Access Protocol for Wireless LAN's," in *Proc. ACM SIGCOMM '94*, pp. 212–25, London, UK, Aug. 31–Sept. 2, 1994 1994.

[3] D. Beyer, "Survivable Adaptive Networks (SURAN) Program," Final Report - Volume III; SRI International, Menlo Park, California, 94025, March 1992.

[4] Beyer, D. (1997): Physical Radio Interface; Rooftop Communications Technical Report (available through http://www.rooftop.com).

[5] D. Beyer, T. Frivold, D. Lancaster, and M. Lewis, "Radio Device API," *Proc. IEEE MILCOM 97*, Monterey, California, November 1997.

[6] J. Boudenant, B. Feydel and P. Rolin, "Lynx: An IEEE802.3 compatible deterministic protocol," *Proc. IEEE INFOCOM '87*, 1987.

[7] J.I. Capetanakis, "Tree algorithm for packet broadcasting channel," *IEEE Trans. Inform. Theory*, vol.IT-25, pp. 505-515, Sept. 1979.

[8] K.-C. Chen, "Medium access control of wireless lans for mobile computing," *IEEE Network*, vol. 8, no. 5, pp. 50–63, 1994.

[9] A. Colvin, "CSMA with collision avoidance," *Computer Commun.*, vol. 6, no. 5, pp. 227–35, 1983.

[10] R. G. Gallager, "Conflict resolution in random access broadcast networks," *Proc. AFOSR Workshop Commun. Theory Appl.*, Provincetown, MA. Sept. 1978.

[11] R. Garces and J. J. Garcia-Luna-Aceves, "Floor acquisition multiple access with collision resolution," *Proc. ACM/IEEE Mobile Computing and Networking '96*, Rye, NY, Nov. 10-12, 1996.

[12] *P802.11–Unapproved Draft: Wireless LAN Medium Access Control (MAC) and Physical Specifications*, IEEE, January 1996.

[13] P. Karn, "MACA - a new channel access method for packet radio," in *ARRL/CRRL Amateur Radio 9th Computer Networking Conference*, pp. 134–40, ARRL, 1990.

[14] L. Kleinrock and F. A. Tobagi, "Packet switching in radio channels: Part I - carrier sense multiple-access modes and their throughput-delay characteristics," *IEEE Trans. Commun.*, vol. COM-23, no. 12, pp. 1400–1416, 1975.

[15] B. M. Leiner, D. L. Nielson, and F. A. Tobagi, eds., *Proceedings of the IEEE*, vol. 75, IEEE, January 1987.

[16] B. Leiner, R. Ruth, S. Ambatipudi, "Goals and Challenges of the DARPA GloMo Program," *IEEE Personal Communications*, Dec. 1996.

[17] W. F. Lo and H. T. Mouftah, "Carrier Sense Multiple Access with Collision Detection for Radio Channels," in *IEEE 13th Int'l Commun. and Energy Conf.*, pp. 244–47, IEEE, 1984.

[18] J. L. Massaey, "Collision resolution algorithm and random access communications," in *Multiuser Communication Systems, G. Longo Ed.*. New York: Spriger-Verlag, 1981. pp. 73-137.

[19] M. J . Karol and I. Chih-Lin, "A protocol for fast resource assignment in wireless PCS," *IEEE Transactions on Vehicular Technology*, vol. 43, no. 3, pp. 727-32, IEEE, 1994.

[20] S. Murthy and J.J. Garcia-Luna-Aceves, "A Routing Protocol for Wireless Networks", *ACM Mobile Networks and Nomadic Applications (MONET)*, Special Issue on Routing in Mobile Communication Networks, 1996.

[21] F. A. Tobagi and L. Kleinrock, "Packet switching in radio channels: Part II - the hidden terminal problem in carrier sense multiple-access modes and the busy-tone solution," *IEEE Trans. Commun.*, vol. COM-23, no. 12, pp. 1417–1433, 1975.

[22] F. A. Tobagi and L. Kleinrock, "Packet switching in radio channels: Part III - polling and (dynamic) split-channel reservation multiple access," *IEEE Trans. Commun.*, vol. COM-24, no. 8, pp. 832–845, 1976.

[23] T. Towsley, and P. O. Vales, "Announced arrival random access protocols," *IEEE Trans. Commun.*, vol. COM-35, no. 5, pp. 513-521, May 1987.

[24] B.S. Tsybakov, and N.B. Likhanov, "Upper bound on the capacity of random multiple access system," *Problems of Information Transmission*, vol. 23, no. 3, pp. 224-236, July-Sept. 1987.

[25] W. Xu and G. Campbell, "A distributed queuing random access protocol for a broadcast channel," *Proc. ACM SIGCOMM '93*, San Francisco, USA, 13–17 Sept. 1993.