

INTRODUCTION BY EDITOR

The following article provides a concise, clearly written discussion of the history of the well-known Aloha protocol by Prof. Norman Abramson, the key individual responsible for its invention, development, and initial deployments in a variety of applications involving joint use of a given medium by potentially interfering systems. He discusses the use of this protocol and its various incarnations, continuing to this day, in such disparate applications as wired Ethernet, satellite communications, and mobile wireless systems, among others. What is, in my mind, so

amazing about this scheme is its basic simplicity, yet profound ability to find application in such a widespread range of communication systems.

The protocol, in its most concise form, says transmit at will. If interference is detected, retransmit some random time later. What can be simpler? Yet, despite its apparent simplicity, such a protocol was not at all obvious at the time of its invention and initial deployment. Enjoy reading this article!

—Mischa Schwartz

THE ALOHANET — SURFING FOR WIRELESS DATA

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INTRODUCTION

The development of the Aloha System project at the University of Hawaii beginning in the late 1960s provides historical insight into a variety of wireless data network applications at the start of the 21st century. In 1971 the Aloha System established and operated a UHF terrestrial data network (AlohaNet) within the state of Hawaii. In 1973 the Aloha System used a VHF transponder in an experimental NASA satellite (ATS-1) to demonstrate an international satellite data network (PacNet) connecting NASA in California and five universities in the United States, Japan, and Australia. Also in 1973 the Aloha System pioneered the unconventional use of a conventional commercial Comsat channel to link the AlohaNet and PacNet to ARPANet in the continental United States.

AlohaNet within Hawaii and PacNet covering the Pacific were both based on the use of a random access channel architecture now generally referred to as an ALOHA channel. Today ALOHA channels are utilized in all major mobile networks and in almost all two-way satellite data networks.

Every time you power up your mobile phone or use that phone to establish a voice, SMS, or Internet connection, the very first packet transmitted is sent via an ALOHA random access channel. The importance of the ALOHA channel within all wireless networks has increased as the utilization of such networks for SMS and Internet traffic has increased. In addition, the initial Aloha System research led directly to the work on carrier sense multiple access (CSMA) at the University of California at Los Angeles (UCLA) which provided the theoretical foundation for both CSMA with collision

detection (CSMA/CD) in Ethernet and CSMA with collision avoidance (CSMA/CA) in WiFi and WiMAX.

This anecdotal account of the development of the Aloha System is based on an invited paper [1] first published in a special issue of *IEEE Transactions on Information Theory* edited by Jim Massey in March 1985 [2].

BACKGROUND

In the late 1960s a number of efforts were in progress to use the existing worldwide telephone network to provide remote access to computer systems for terminals and, in some more ambitious cases, to provide connections among large information processing systems for resource sharing. The term “resource sharing” at that time was often taken to mean a sharing of hardware that would be considered primitive by today’s standards. Nevertheless, in 1968 it was becoming apparent that the existing circuit-switched telephone network architecture was not well suited to the rapidly emerging data networking needs of the 1970s. Indeed, it would have been surprising had such a network architecture, shaped by the requirements of voice communications at the end of the 19th century [3], been compatible with the emerging requirements of data communication networks at the end of the 20th century. The original goal of the Aloha System was to investigate the use of radio communications as an alternative to the telephone system for computer communications and to “determine those situations where radio communications are preferable to conventional wire communications” [4].

At that time the University of Hawaii was composed of a main campus in Manoa Valley near Honolulu, a

four-year college in Hilo, Hawaii, and five two-year community colleges on the islands of Oahu, Kauai, Maui, and Hawaii, all within a radius of about 300 km from Honolulu. In September 1968 a faculty group in the Department of Electrical Engineering at the University of Hawaii began to plan for an experimental radio-linked computer network to connect all of these locations together in order to permit sharing of the computer resources on the main campus. Even after the decision to build a radio data network, however, a number of basic design decisions dealing with the choice of network architecture had to be addressed. From the beginning it was clear that the nature of the radio channel provided new system design options not available in systems using conventional point-to-point telephone channels. As the network planning proceeded, this key point assumed greater and greater significance. It would be gratifying to be able to report that this key difference between radio channels, with broadcasting and multiple access capabilities, and conventional point-to-point wire (or microwave) channels was appreciated as we began the project. Unfortunately, such an appreciation developed among the members of the project only with time. As is the case in many real-world situations, our foresight was not as clear as our hindsight.

Even at the beginning of the project, however, it was understood that the intermittent operation typical of interactive computer terminals was a convincing argument against the assignment of point-to-point channels in a conventional frequency-division multiple access (FDMA) or time-division multiple access (TDMA) manner. Some more efficient form of sharing a common communication channel

resource appeared necessary. The classical spread spectrum techniques of direct sequence spreading or frequency hopping seemed to be one way of sharing channel resources, and a spread spectrum architecture was considered for the system. But the implementation of a spread spectrum format in each user terminal at a useful data rate and at a reasonable cost seemed a formidable task in 1969, given the existing state of technology.

SYSTEM DESIGN

The first year of the project was spent in the study of the above questions, the specification of a number of basic system parameters (e.g., frequency band, bandwidth, data rate), and the organization of a laboratory for both the radio and digital circuit parts of the system. In addition to me, the faculty involved in the project at that time included Thomas Gaarder, Franklin Kuo, Shu Lin, Wesley Peterson, and Edward Weldon. The key decision to use the direct form of transmitting user information in a single high-speed packet burst in a shared channel, now known as an ALOHA channel, was made at a meeting of the project participants in 1969. The operation of the channel was not well understood at that time, and the derivation of the throughput of an ALOHA channel [4] was to come only several weeks after the decision to use that channel. Nonetheless, the criterion of design simplicity which led to that decision should not be underestimated as a reliable guide to designing data networks that work.

The remaining system design decisions were easier to make. In retrospect, the only one that was crucial from the point of view of getting some sort of acceptable system operation was the choice of frequency band. That decision was made on the basis of some helpful advice from Dr. David Braverman of Hughes Aircraft Company. AlohaNet was assigned two 100 kHz bandwidth channels at 407.350 MHz and 413.475 MHz, and, after the usual unexpected software delays, the first ALOHA random access user terminals went into operation in June 1971. Formatting of the ALOHA packets as well as the retransmission protocols used in the AlohaNet were implemented by a special-purpose piece of equipment (designed by Alan Okinaka and David Wax) called the terminal control unit (TCU) (Fig. 1). A user terminal was attached to the TCU by means of a standard RS232 interface, and the user was connected to the central University



Figure 1. ALOHA TCU 1971.

of Hawaii IBM computer at a data rate of 9600 bs anywhere within range of the radio system (about 100 km for the AlohaNet).

The design of the original TCU was constrained by the need to provide extensive debugging tools in this first random access packet interface and by the technology of the times. Some understanding of the distance we have traveled since then may be obtained by considering how one key decision in the design of the original network was affected by the cost of memory. It was generally understood in the project that a full duplex mode of operation for the TCU would be desirable from the point of view of both system protocols and simpler hardware design. Full duplex operation, however, required the use of two independent buffers to store the packets flowing into and out of the TCU, and at that time the cost of memory for an additional packet buffer of 88 bytes was about \$300. We decided that full duplex operation was not important enough to justify that expenditure, since we were interested in a network that might eventually contain hundreds of user stations. As a point of comparison, I recently purchased a USB memory stick with 16 Gbytes storage for about \$40 — a decrease in the price per bit of storage by a factor of more than 1 billion in 40 years.

During 1971 and 1972, as additional TCUs were built and a network came into existence, our understanding of the distinction between point-to-point channels and random access/broadcast channels deepened. It became clear that the key innovation of the AlohaNet was not just the first use of wireless communications for a data network, but at a deeper

level it was the use of a random access/broadcast communications architecture for network communications. Furthermore, we began to understand that the advantages we were seeing in our network could be obtained in any network with intermittent (bursty) transmitters as long as the bursty network traffic flowed in a random access channel. The imminent launch of domestic communication satellites by the United States (Westar I was launched in 1974) suggested the use of a random access architecture for satellite networks, and we turned our attention to the use of ALOHA channels in satellite systems at about that time [5, 6].

SATELLITE NETWORKS

As one step in this process, it was decided to obtain a satellite link to connect the AlohaNet in Hawaii to the rapidly expanding ARPANet packet-switched network on the U.S. mainland. The Aloha System funding at about this time was transferred to the Advanced Research Projects Agency (ARPA), under the direction of Dr. Lawrence Roberts, and the connection to the ARPANet seemed sensible for a variety of reasons.

When the initial contacts with possible carriers were made in order to lease a 56 kb/s satellite channel for the connection from the AlohaNet to a node of the ARPANet at NASA Ames Research Center in California, it was suggested that we lease 12 satellite voice channels under existing tariffs for voice grade channels, interface each of these channels with a modem operating at 4800 bs, and multiplex the outputs to obtain the data rate desired. Such a procedure had obvious economic bene-



Figure 2. ALOHA PCU 1973.

fits to those providing the 12 leased satellite channels, but it also required that ARPA lease 12 satellite voice channels to send only 56 kb/s. The leasing of 12 voice channels seemed wasteful when we pointed out that the standard COMSAT technique for transmitting a single voice channel at that time was to transform the analog voice signal into a 56 kb/s pulse code modulation (PCM) data signal at the Earth station. In other words, the existing tariff structure would have had us convert our 56 kb/s data signal into 12 4800 b/s signals for transmission to the satellite Earth station on the north shore of Oahu, where these channels would have been transformed into 12 56 kb/s signals, transmitted to the other Earth station in California as 12 56 kb/s signals, and transformed back into 12 4800 b/s signals for delivery to the network. These signals would then be multiplexed to form the 56 kb/s data stream desired. It is a pleasure to report that common sense finally prevailed, and after some discussions with Roberts, a new 56 kb/s tariff was introduced by COMSAT (which showed up in the COMSAT annual reports for several years as the "ARPA tariff") allowing the lease of digitized 56 kb/s channels as data channels.

The ARPA/Aloha System link was the first commercial satellite link to employ a single satellite voice channel permitting a user to transmit 56 kb/s of network data. However, this channel was not operated in a random access mode by COMSAT, but in a conventional point-to-point mode. The first network to utilize random access packet transmission in a satellite channel was put into operation in the Aloha System in 1973, using the ATS-1 satellite in an experimental network that included the University of Hawaii, NASA Ames Research Center in California, the Uni-

versity of Alaska, Tohoku University in Sendai, Japan, the University of Electro-communications in Tokyo, and the University of Sydney in Australia. This network, called PacNet, operated at 9600 b/s in an ALOHA channel using low-cost satellite Earth stations to show the potential of data networks with large numbers of small Earth stations [7].

Financial support for the research on the Aloha System while the AlohaNet and PacNet were being built, and these two networks were connected to the ARPANet in the continental United States was provided by the Information Processing Techniques Office of ARPA, under the direction of Larry Roberts. In addition to this financial support of the Aloha System, Roberts also contributed to the success of the project in a way not ordinarily obtained from funding agencies. In a real sense, Roberts acted as another member of the research staff of the project, contributing a number of major technical results (including the first derivation of the capacity of the slotted ALOHA channel and the first analysis of capture effect in ALOHA channels [8]).

Sometime in 1972, I was visiting Roberts' office in Washington for discussions dealing with both technical and administrative matters in the Aloha System when he was called out of his office for a few minutes to handle a minor emergency. 1972 was a year of rapid growth for the ARPANet as the interface message processors (IMPs) that defined the nodes of the network were installed in the first network locations. While waiting for Roberts' return, I noticed on the blackboard in his office a list of the locations where ARPA was planning to install IMPs during the next six-month period, together with the installation dates. Since I planned to bring up the question of installation of

an IMP at the Aloha System laboratory in Hawaii to be used with the satellite channel discussed above, I took the chalk and inserted "the Aloha System" in his list and beside it placed the date of December 17 (chosen more or less at random). After Roberts' return, we continued our discussion but, because of the rather long agenda, we did not discuss the installation of an IMP in Hawaii, and I forgot I had inserted an installation date of December 17 for us in the ARPA schedule on his blackboard. I never did get the opportunity to discuss the installation of an IMP in our laboratory with Roberts. Instead, about two weeks before the December 17 date, we received a phone call from the group charged with the responsibility of installing the IMPs asking us to prepare a place for the equipment. On December 17, 1972, an IMP connecting the ALOHA system and AlohaNet to the ARPANet by means of the first satellite channel in the ARPANet was delivered and installed.

By 1974, with the advent of the first microprocessors by Intel, it was clear that much of the logic of the TCU could be handled by a microprocessor, and several new terminal controllers, based on the INTEL 8080, were designed by Christopher Harrison and put into operation. Because the network protocols could now be implemented in software, and this software could be simultaneously modified for all operating units by having the central station broadcast new protocol parameters or even a completely new protocol, these new controllers were called programmable control units (PCUs) (Fig. 2). Once the basic protocols of the ALOHA channel were analyzed and demonstrated in the AlohaNet UHF radio channels, it was not long before other groups began to look into the possibility of using ALOHA random access in other media as well. One of the first and most successful of these efforts was begun in the doctoral dissertation of Robert Metcalfe at Harvard University published as a project MAC report at the Massachusetts Institute of Technology (MIT) [9].

COMMERCIAL APPLICATIONS

ALOHA in Cable and Fixed Wireless Networks: Bob Metcalfe was probably the first person to appreciate the significance of the distinction between the communications architecture of point-to-point circuit-switched and packet-switched data networks and the random access/broadcast architecture of the AlohaNet. In his doctoral dissertation

he coined the term “packet broadcasting” to emphasize this distinction, although the term “random access” is typically used to describe that communications architecture today. When his dissertation was complete, he spent several months with the Aloha System at the University of Hawaii, working with Richard Binder who had developed and implemented the ALOHA software and network protocols [10]. After leaving Hawaii, Metcalfe joined the Xerox Palo Alto Research Center, where his development of Ethernet (with David Boggs) demonstrated the effectiveness of a random access architecture on a cable-based medium. The first 3 Mb/s Ethernet implemented at Xerox was initially called the Alto ALOHA Network [11]. Metcalfe then worked with DEC, Intel, and Xerox (the DIX group) to establish an open CSMA/CD standard for a 10 Mb/s Ethernet and commercialized this standard after leaving Xerox to found 3COM Corporation.

The UHF frequencies used in the ALOHAnet were obtained as a temporary experimental license authorized by the FCC as part of the ARPA program funding our university-based research. In the early 1970s after we had built the network, experimented with a wide variety of network applications (including packet repeaters, sensor networks, and internet-working), and developed a theoretical foundation for many of these applications [12], it was not at all clear how to convince the appropriate regulatory authorities to provide the frequencies necessary for the commercial development of wireless ALOHA technology.

In the late 1970s Michael Marcus, a staff member at the U.S. Federal Communications Commission, proposed the establishment of unlicensed spread spectrum bands in the United States [13]. After a good deal of discussion, on May 9, 1985 the Commission established rules for the unlicensed use of spread spectrum systems to operate in the industrial, scientific, and medical (ISM) bands at 902–928, 2400–2483.5, and 5725–5850 MHz on a noninterfering basis to other authorized users of these bands [14]. Other countries followed the lead of the U.S. FCC in authorizing these bands for unlicensed transmission of data. In 1997 the IEEE 802.11 standard for WiFi was established using CSMA/CA for wireless access [15] using the ISM bands. The issue of frequency availability was not an issue in the design of random access for cable-based data networks. The cable-based DOCSIS standard [15, 16] uses a slotted ALOHA channel for both Internet and voice

packets. The initial random access packet in DOCSIS is used to set up a temporary reservation channel as in General Packet Radio Service (GPRS).

ALOHA in Satellite Networks: The first use of ALOHA random access in an operational commercial satellite network took place shortly after the Ethernet effort in the COMSAT Marisat system in 1976 [17]. The request channel used to allocate voice and telex channels in Marisat required some technique capable of sharing a single low-speed (4800 bs) channel among hundreds of possible users, and an unslotted ALOHA channel was chosen. Much of the theoretical foundation for both the cable-based and satellite-based systems was developed at about the same time by Kleinrock, Tobagi, and Lam at UCLA [18–20]. Once these developments took place, it was astonishing how rapidly the acceptance of ALOHA-based medium access control (MAC) protocols proceeded. By 1977, at least one book had been published that referred to the unslotted ALOHA channel as the “classical ALOHA channel” [21, p. 587].

Today satellites in geostationary orbit provide data transmission services to several million small Earth stations around the world. In almost all cases, whenever these earth stations are used for two-way data, network access is provided by ALOHA or slotted ALOHA. Many of these networks are private networks for companies in retailing, publishing, and the financial industry or for governments; other satellite data networks using ALOHA are public networks providing general Internet access such as HughesNet and WildBlue. Both HughesNet and WildBlue use slotted ALOHA for traffic in the multiple access channel. More recently both ViaSat and Ceron have used Spread ALOHA [22] for more advanced satellite networks.

ALOHA in Mobile Networks: It is convenient to characterize the introduction of ALOHA channels in wireless mobile networks by recalling the state of technology, and of telecommunication regulation, during each of the past few decades. In the early 1970s both ALOHAnet and PacNet went into operation, providing a clear demonstration of the practicality and efficiency of this type of wireless network architecture for user generated bursty data. Later in the 1970s Ethernet and the Comsat Marisat network provided the first examples of ALOHA random access in commercial networks.

Although the basic concepts of cellular telephone technology had been under development at Bell Labs (and in

Europe and Japan as well) in the 1970s, it was not until 1982 that the U.S. FCC allocated frequencies for establishing such a system [23]. At the beginning of the 1980s there were limited options available for wireless transmission of data. Two of the most important networks of that era were ARDIS and Mobitex, both operating in the 800–900 MHz range and both providing an initial data rate of 8 kb/s. ARDIS was a joint venture by IBM and Motorola based on an unslotted ALOHA channel and initially utilized primarily by IBM service technicians; Mobitex was developed by Ericsson and Swedish Telecom based on a slotted ALOHA channel implemented in Europe and (by RAM Mobile Data) in the United States [24]. But by the end of the 1980s it was becoming clear that effective development of wireless data networks should be included within the burgeoning worldwide cellular mobile phenomenon.

The first commercial deployment of a first-generation (1G) mobile network in the United States was AMPS in Chicago in 1983. AMPS was based on an analog architecture, but the request channel for AMPS was implemented as an unslotted ALOHA channel for initiating call connections [25]. Similar networks were deployed in that time period in both Europe and Japan. Remember that the set of applications suitable for a pervasive data network in the early 1980s was limited. The IBM PC was announced in August 1981. In December 1981 I purchased one of the first IBM PC's sold in Hawaii including an IBM modem board and some primitive (but open) software to allow me to connect to the Hawaiian telephone network at 300 b/s.

The 2G mobile networks that started to appear in the 1990s (GSM in Europe, IS-54 and IS-95 in the United States) were digital networks which initially used ALOHA only for the request channel — slotted ALOHA in all cases.¹ The use of ALOHA packets for

¹ It should be noted that the spread spectrum IS-95 system employed what can be called a spread spectrum ALOHA channel in that both spread spectrum and ALOHA properties were used in the request channel for IS-95. This spread spectrum ALOHA channel should be differentiated from the Spread ALOHA channel [1, 22] in that IS-95 still uses different spreading sequences to separate different requesting transmitters in the random access channel while the Spread ALOHA channel employs the same spreading sequence for all transmitters in the random access channel.

requests and signaling applications within the mobile voice network suggested the use of ALOHA packets for user traffic as well, so by the beginning of the new century user traffic was handled in a variety of 2G or 2.5G networks by GPRS [23] using a slotted ALOHA random access channel combined with a version of the Reservation ALOHA scheme first analyzed by a group at BBN [26].

The first 3G mobile networks were introduced in Japan in late 2001 and in Korea in early 2002. The first 3G mobile networks in Europe began commercial operation in 2002, while service in the United States began in late 2003. Both wideband code-division multiple access (W-CDMA) and cdma2000 provide the higher bit rates and increased emphasis on packet mode traffic required in the networks of today [23, 27]. ALOHA provides a natural choice of network architecture for this kind of traffic, and the designs of both these 3G networks reflect an increasing use of ALOHA random access for user packet data as well as for signaling and control purposes.

As this is written on the threshold of the 2010s, the shape of the implementation of 4G mobile wireless is not clear, but it does seem clear that an increased emphasis on packet data services, always connected response times, and higher data rates will lead to increased use of ALOHA random access in 4G wireless mobile networks.

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BIOGRAPHY

NORMAN ABRAMSON [F] received an A.B. in physics from Harvard College in 1953, an M.A. in physics from UCLA in 1955, and a Ph.D. in electrical engineering from Stanford in 1958. He was an assistant professor and associate professor of electrical engineering at Stanford from 1958 to 1965. From 1967 to 1995 he was professor of electrical engineering, professor of information and computer science, chairman of the Department of Information and Computer Science, and director of the ALOHA System at the University of Hawaii. He is now professor emeritus of electrical engineering at the University of Hawaii. He has held visiting appointments at the University of California at Berkeley, Harvard, and MIT (1965, 1966, 1980). He is a fellow of the IEC. He is also the recipient of the IEEE Sixth Region Achievement Award, the PTC 20th Anniversary Award, the IEEE Koji Kobayashi Computers and Communications Award, the IEEE Information Theory Society Golden Jubilee Award for Technical Innovation, the Eduard Rhein Foundation Technology Award, and the IEEE Alexander Graham Bell Medal.