A Brief Survey of Technological Innovation in Amateur Radio

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Abstract

In recent decades, the perception of Amateur Radio within the general public has shifted from Amateur Radio being useful, innovative, and an interesting technical activity, to Amateur Radio being perceived as an anachronism and largely irrelevant (except in the direst of communications emergencies). Summarized: "Ham Radio – that's still around?"

Amateur Radio's service to the public for emergency communications is being supplanted by improved commercial and government communications capabilities such as improved Iridium[2] satellite phones, the FirstNET[3] public safety cellular system, and most recently, the nomadic capability of the Starlink[4] broadband satellite system.

Amateur Radio has continuously developed unique technological innovations in radio technology, and that has not only continued in the modern era but has *accelerated*. However, that ongoing, unique contribution to technological society is, increasingly, unrecognized. That is unfortunate. *If* regulators, lawmakers, industry, the general public… and the Amateur Radio community itself understood the unique contributions to technological innovations in radio technology that Amateur Radio continues to develop, perhaps such recognition might improve Amateur Radio's perception that it remains a valuable part of society, worthy of continued access to portions of the electromagnetic spectrum.

Keywords

Amateur, Radio, Operator, Ham, Wireless, Technology, Innovation, Spectrum, Digital, VHF, UHF, SHF, Microwave, Communications, ARDC, Techies, Makers, Hackers, Zero Retries Newsletter, Experimentation, Research and Development, FlexRadio, Steve Stroh N8GNJ

Background

For decades, I have been an admirer of technological innovation in Amateur Radio. Not just new technologies like Packet Radio emerging in the 1980s, but new techniques for old problems such as digital techniques enabling reliable communications via unreliable mediums such as the High Frequency (HF)[5] (aka Shortwave) portions of the electromagnetic spectrum.

Amateur Radio's unique culture, the varying characteristics of various portions of spectrum allocated to (or shared with) Amateur Radio operations, and the many highly capable and skilled Amateur Radio Operators, have resulted in a fertile, and welcoming "experimental zone" for technological innovation in radio technologies. Until recent decades, that culture of technological innovation was widely recognized, and encouraged. In the last few decades, the recognition of

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[1] Email – stevestroh@gmail.com
[2] https://www.iridium.com/network/
[3] https://firstnet.gov/network
[4] https://www.starlink.com/rv
[5] https://en.wikipedia.org/wiki/High_frequency

A Brief Survey of Technological Innovation in Amateur Radio

Amateur Radio's utility and contributions to technological innovation have been deprecated to near irrelevence… at least in popular perception… by ubiquitous Internet access, mobile phones, caricatures of Amateur Radio as "Grandpa sitting in the basement tapping on a Morse Code key", and most notably, the removal of old barriers to individuals communicating across international borders.

A primary reason that this is a concern for society is that it has become irrevocably dependent on radio technology as the primary method of communications for mobile devices, most notably cellular technology, wireless local area networks (Wi-Fi), and most recently, direct-to-user satellite communications. For many people, their mobile phone is their only method of communications and media consumption. Much of that technology has been developed and manufactured in China. Dependence on China for such a critical infrastructure function is proving to be fraught with peril. To counter that peril, the US and other Western nations must quickly develop additional expertise, and personnel, "in nation" to better develop and support this now-critical wireless infrastructure. Amateur Radio can be a "training ground" for developing familiarity and expertise with radio technology, leading to careers in developing and supporting radio technology… but only if Amateur Radio is recognized as a useful and interesting.

The rise of technology specialists, especially those trained in Information Technology (IT), the "Maker culture"[6], and the "Hacking Culture"[7] have breathed new life into Amateur Radio. "Techies" have discovered Amateur Radio as an enabling technology for supporting experimentation with Information Technologies (such as building hobbyist / not-for-profit wide-area microwave networks). Makers have discovered that there are incredibly interesting things that they can add to their personal knowledge base and practical projects based on capabilities Amateur Radio has long taken for granted, such as long-range communications via VHF / UHF repeaters. Hackers have discovered Amateur Radio as a fertile "playground" for their experiments and expansion of knowledge about radio technology, such as Software Defined Receivers… and Transmitters (*with* an Amateur Radio license).

I started the Zero Retries Newsletter[8] in July, 2021 out of frustration that the totality of technological innovation in Amateur Radio wasn't being recognized by the Amateur Radio community, its regulators, and especially the public at large. Specifically, I was worried about the growing public perception that Amateur Radio is irrelevant, or worse, an anachronism. Such a perception, if it is to continue for much longer, may prove catastrophic to Amateur Radio, most notably in the loss of Amateur Radio access to various portions of spectrum. To date I've published more than fifty weekly issues of Zero Retries, and each issue highlights some aspect of technological innovation in Amateur Radio.

Literally, Amateur Radio is a license to experiment with radio technology and a welcoming "innovation zone" to develop new and exciting technological innovations in radio technology. I hope to make that point with the vignettes in this paper.

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[6] https://en.wikipedia.org/wiki/Maker_culture
[7] https://en.wikipedia.org/wiki/Hacker_culture
[8] https://zeroretries.substack.com (will eventually migrate to https://zeroretries.org)

Amateur Radio Digital Communications[9]

One of the most significant factors regarding technological innovation in Amateur Radio is the recent emergence of Amateur Radio Digital Communications (ARDC)[10] as a funding source for innovative projects and organizations. Many promising Amateur Radio projects die out before completion because of lack of resources, especially expensive and unavailable expertise in radio frequency engineering, requirements for expensive test equipment, "only professionals can afford it" design software, the expense of prototype manufacturing, etc.

ARDC was formed to manage 44Net[11], the Class A Internet Protocol v4 Internet address block of ~16 million contiguous IPv4 addresses. A few years ago, ARDC sold a contiguous block of ~4 million IPv4 addresses, and with the proceeds of that sale, reorganized itself as a private foundation and created an endowment fund. ARDC invested its endowment prudently, and from that investment it distributes 5% (minimum) annually of its endowment in the form of grants[12], funds the minimal expenses of the organization including staff, contractors, and overhead, and continues to operate 44Net.

By mid-2021, ARDC was fully staffed, including a volunteer Grants Advisory Committee, and since then has funded many grants, large and small[13]. While ARDC isn't the only grant making organization focused on Amateur Radio, ARDC is unique in the size and scope of its grants to Amateur Radio. The grants that ARDC provides can be transformational to organizations and projects. Listed below are a few grants that reflect the technological innovation in Amateur Radio that ARDC grants are empowering:

- ARDC's largest grant to date was $1.6 million to repair and refurbish "**The Big Dish**" at Massachusetts Institute of Technology (MIT)[14]. This dish was originally installed on the roof of the 22-story Green Building on the MIT campus to develop weather RADAR technology. After that project was complete, the dish was turned over to the MIT Radio Society (Amateur Radio club) for experimentation. The dish has been used for Earth Moon Earth (EME) communications, radio astronomy, Amateur Radio VHF / UHF / Microwave contesting, and many other innovative experiments. The Green Building was slated for renovation, including the roof, and MIT planned to remove the dish. The MIT Radio Society was able to convince MIT to give them a chance to raise private funds for the repair and refurbishment of the dish, including a new fiberglass radome. With only a few months before the Green Building work was to commence, approximately $300,000 of the required $1.9 million had been raised. Fortunately, ARDC was able to step in with the balance of funds needed, and with the required funds secured, "The Big Dish" will be returned to the roof of the Green Building including all required structural updates, a new radome, new mechanicals, etc.

[9] Disclaimer – In 2021 and 2022, the author is a volunteer member of ARDC's Grants Advisory Committee. The views expressed here are his own, not intended to reflect, or speak for, the views of ARDC. This paper is written entirely independent of ARDC.
[10] https://www.ampr.org
[11] https://wiki.ampr.org/wiki/Main_Page
[12] https://www.ampr.org/grants/
[13] It should be noted that ARDC grants have also funded numerous projects for Amateur Radio clubs (such as new stations, new repeaters, new trailers, professional tower climbing), funded numerous scholarships, and funded research and development projects (unrelated to Amateur Radio), and significant assistance to Open Source work.
[14] https://www.ampr.org/grants/2021-grants/grant-mit-radio-society-radome-renewal/

- **Amateur Radio on the International Space Station (ARISS)**[15] has received several ARDC grants, including an early grant to help fund the ARISS Next Generation Radio[16] and a five-year $1.3 million grant[17] to develop new curriculum material and hands-on experiments for classroom Science, Technology, Engineering, Arts, and Math (STEAM) lessons that can be provided to teachers in conjunction with space studies.
- Although not specific to Amateur Radio, **GNU Radio Project**[18] is a vibrant, Open Source project for Software Defined Radio that is used widely for commercial and academic research, as well as independent experimentation. GNU Radio significantly influences and enhances Amateur Radio and is undeniably a source of technological innovation. It's sometimes said that if you "can't do [a radio technology] in GNU Radio… it can't be done - *yet*". ARDC provided an early grant[19] to GNU Radio Project, but its most recent grant[20] is particularly notable in funding usability improvements for GNU Radio, including improvements to the Windows OS version, and documentation improvements.
- The **M17 Project** is an international coalition of volunteers whose goal is to create an Open Source ecosystem for Digital Voice for radio communications – software, hardware, on-air protocols, networking, etc. Think of D-Star[21] or Digital Mobile Radio (DMR)[22] but with only Open Source technology, including the use of Codec 2[23] vocoder subsystem (that in D-Star and DMR is implemented with a proprietary technology). An ARDC grant[24] enabled the M17 Project to purchase test equipment and other significant expenses incurred in development. One project of the M17 Project is development of Mini17[25], an Open Source low-power portable radio.
- **Rhizomatica** is a not-for-profit organization that develops communications systems applicable for the developing world such as parts of South America that do not have commercial communications infrastructure. Rhizomatica makes interesting use of HF technology and an ARDC grant[26] has enabled it to further develop Open Source solutions for expensive, proprietary systems such as higher speed modems used on HF.
- An ARDC grant funded a first of its kind "Amateur Radio Universal Online Library" within the Internet Archive[27] called **Digital Library of Amateur Radio & Communications**[28]. Such a project is expansive, intended to create a universal, searchable resource on Amateur Radio literature, software, radio information, publications, etc. This is coming just in time as many Amateur Radio Operators are "aging out" and much of their valuable and unique data is disappearing as their estates are liquidated. While it will be years before DLARC will emerge as a useful resource, but DLARC, will soon be a place to donate such information so it can be preserved for posterity.
- Most (all?) Amateur Radio satellites to date have used solar panels bonded to their structure, because moving parts in space are hard to engineer and if it breaks, it cannot

[15] https://www.ariss.org
[16] https://www.ampr.org/grants/2019-grants/grant-ariss-next-generation-radio/
[17] https://www.ampr.org/grants/2021-grants/grant-ariss-usa-program/
[18] https://www.gnuradio.org
[19] https://www.ampr.org/grants/2020-grants/grant-gnu-radio-project/
[20] https://www.ampr.org/grants/2022-grants/grant-gnu-radio-usability-enhancements/
[21] https://en.wikipedia.org/wiki/D-STAR
[22] https://en.wikipedia.org/wiki/Digital_mobile_radio
[23] https://en.wikipedia.org/wiki/Codec_2
[24] https://www.ampr.org/grants/2021-grants/grant-m17-open-protocol/
[25] https://github.com/M17-Project/Mini17
[26] https://www.ampr.org/grants/2021-grants/grant-digital-hf-telecommunications-for-civil-and-amateur-uses/
[27] https://archive.org
[28] https://www.ampr.org/grants/2021-grants/grant-building-the-digital-library-of-amateur-radio-communications/

be repaired. An ARDC grant[29] to **AMSAT**[30] is funding the development of a 3U satellite frame with deployable solar panels that will provide the electrical power required higher power operations in highly elliptical orbits that will be used by future AMSAT satellites.
- In conjunction with Ham Radio Science Citizen Investigation (HamSCI)[31], TAPR[32] is developing the **TangerineSDR**[33] [34] [35] [36], an Open Source modular HF radio that will be used, in part for HamSCI's scientific investigation of High Frequency (HF) radio propagation and other scientific experiments.
- Another new radio system under development is the **RPX-100**[37] being developed by the Austrian Amateur Radio Society (ÖVSV)[38]. The RPX-100 will operate on the 50-54 MHz (6 meter band), 144-148 MHz (2 meter band) and 430-450 MHz (70 centimeter band) using new protocols and high speeds. An ARDC grant[39] will help accelerate this project.

Again, the projects mentioned here are only a few highlights (of *many* grants) to emphasize the transformative and accelerative effect that ARDC grants are enabling for technological innovation in Amateur Radio (and related radio technology fields).

It's hoped that in the coming years, ARDC can apply its resources to support even more technological innovation in Amateur Radio, such as supporting the use of FCC Special Temporary Authority authorizations and Part 5 Experimental licenses, coordinating large scale testing of new paradigms in Amateur Radio for potential regulatory updates, coordinating standards bodies of Amateur Radio vendors, etc.

Amateur Radio Integration with Internet

As mentioned in the previous section, Amateur Radio was granted early access to the Internet, and there have been numerous technological innovations resulting from that long experience and familiarity with synergies that can be applied between radios and Internet, such as Winlink (mentioned in the next section).

Brandmeister

Brandmeister[40] is a decentralized network for Amateur Radio digital voice repeaters that encourages experimentation. A significant feature of Brandmeister is that *multiple digital voice systems* (not just Digital Mobile Radio – DMR) are "co-equal" on Brandmeister. Another feature is that text messaging and position beaconing is not just possible on Brandmeister – it's encouraged. (Text messages and position beaconing are often not allowed on some [more fragile] Amateur Radio digital voice networks.)

Networks of Radios Via Internet

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29 https://www.ampr.org/grants/2022-grants/grant-develop-a-3u-open-source-cubesat-space-frame-with-deployable-solar-panels/
30 https://www.amsat.org
31 https://hamsci.org
32 https://tapr.org
33 https://tangerinesdr.com
34 https://www.ampr.org/grants/2020-grants/grant-tapr-tangerinesdr-prototype-build/
35 https://www.ampr.org/grants/2021-grants/grant-tangerinesdr-test-fixtures/
36 https://www.ampr.org/grants/2022-grants/grant-tangerinesdr-project-advancement/
37 https://rpx-100.net
38 https://oevsv.at/home/
39 https://www.ampr.org/grants/2022-grants/grant-wireless-regional-area-network-in-sub-ghz-bands-as-last-mile-for-hamnet/
40 https://wiki.brandmeister.network/index.php/What_is_BrandMeister

A Brief Survey of Technological Innovation in Amateur Radio

As discussed earlier in this paper, Amateur Radio was *early to experiment with integrating radios via the Internet* because of the early allocation of 44net. There are *many* Internet-connected networks of Amateur Radio units, including innumerable networks of repeaters such as Brandmeister (mentioned previously). It's notable that such networks are built and maintained on a non-commercial basis, mostly for the use by Amateur Radio Operators:

- **aprs.fi**[41] – Largest and best-known website for displaying aggregated APRS position, weather, and other tactical information from Amateur Radio stations.
- **AREDN** (mentioned in the next section) provides optional Internet connectivity, largely as "training wheels" to help new AREDN users get familiar with AREDN and remain connected to other AREDN users in their area, in preparation for getting an AREDN node on the air.
- **Personal Space Weather Station (PSWS)**[42] – Project of Ham Radio Science Citizen Investigation (HamSCI) to develop a network of radio receivers and other instruments such as magnetometers.
- **PSK Reporter** (Digimode Automatic Propagation Reporter)[43] – Network of receivers monitoring Amateur Radio data transmissions on HF.
- **Receiverbook**[44] – Directory of online Software Defined Receivers available for public use.
- **Reverse Beacon Network**[45] – Transmit on HF and see where your transmission was heard worldwide.
- **SatNOGS**[46] – Network of receivers focused on tracking and receiving low earth orbit (LEO) research satellites, especially those built by students. SatNOGS stations track satellites, download data locally, do some local processing, and then upload the raw and processed data for the researchers. Ground stations can be built relatively inexpensively, including some parts for the tracking hardware that can be 3D printed. SatNOGS is not entirely Amateur Radio.
- **SondeHub**[47] – Network of receivers that monitor weather radiosonde[48] transmitters, and radiosondes repurposed for Amateur Radio use.
- **Weak Signal Propagation Reporter Network (WSPRNet)**[49] – Monitors for WSPR transmissions and displays where your WSPR transmission was heard, worldwide.
- **WebSDRs**[50] – A WebSDR is a Software Defined Receiver connected to the Internet, allowing many listeners to listen and tune it simultaneously. SDR technology makes it possible that all listeners tune independently, and thus listen to different signals on different frequencies. There are *many* SD Receivers available for use on the Internet, findable via this page.

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41 https://aprs.fi
42 https://hamsci.org/basic-project/personal-space-weather-station
43 https://pskreporter.info
44 https://www.receiverbook.de
45 http://www.reversebeacon.net/
46 https://satnogs.org/
47 https://sondehub.org
48 https://en.wikipedia.org/wiki/Radiosonde
49 http://wsprnet.org/drupal/
50 http://www.websdr.org

Multipurpose Remote Nodes (MRNs)

Several Multipurpose Remote Nodes (MRNs)[51] have been deployed in Whatcom County (Bellingham area), Washington USA. MRNs are unique in that they are located at remote sites, are connected to Internet, and their usage and radio parameters can be reconfigured remotely. While each MRN has a primary function – Winlink Radio Mail Server (RMS) on VHF / UHF[52], APRS Digipeater[53] and Igate[54], or fldigi (fsq mode)[55] relay, they can be remotely reconfigured as needed.

RadioID.net

Sometimes the complicated things can get fixed by applying the right idea. Digital Mobile Radio (DMR) was intended as a radio system for organizations, and thus each DMR *system* is licensed (such as a factory), not individual radios or users. When Amateur Radio began using DMR, one of the first issues with using DMR in Amateur Radio was that DMR radios transmit only "ID numbers"; there was no requirement to transmit a callsign. Thus, a database had to be established to issue, and cross reference DMR ID numbers to Amateur Radio callsigns. But, being modern Amateur Radio Operators, we quickly started to network DMR repeaters, and thus found the second major "Amateur Radio deficiency" of DMR – it was easy to create duplicate ID numbers, which can play havoc with routing within networks of DMR repeaters. As DMR usage became more common in Amateur Radio, various databases of Amateur Radio DMR IDs were established for various communities (such as Motorola DMR users). However, *keeping* those databases consistent and synchronized was problematic and time consuming. Eventually, a single, authoritative database of Amateur Radio (and other) DMR IDs emerged that was universally accessible via the Internet - RadioID.net[56].

Amateur Radio *Radio* Technological Innovation

Some might argue that it's harder to create new radio technologies in this era, but if so, there's still ample technological innovation occurring in Amateur Radio in the development of new radio units and systems. Besides the examples of radio development funded by ARDC grants, these are a few examples of *radio* technological innovation.

Amateur Radio Emergency Digital Network (AREDN)

AREDN[57] is an outgrowth of earlier projects to repurpose commercial microwave communications units such as Wi-Fi access points and microwave equipment intended for use by enterprises and Wireless Internet Service Providers (WISPs).

AREDN firmware was originally based on OpenWRT[58] but has diverged significantly from that technology as AREDN has been optimized for use in Amateur Radio. Notably, there have been three significant AREDN firmware releases to date in 2022.

AREDN develops replacement firmware for these units that add features specific for Amateur Radio use, including:

- Use of semi-exclusive portions of spectrum allocated to Amateur Radio,

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[51] https://zeroretries.substack.com/p/zero-retries-0010
[52] https://www.winlink.org/content/rms_packet
[53] http://www.aprs.net.au/vhf/aprs-digipeaters-101/
[54] http://www.aprs-is.net/igating.aspx
[55] http://www.w1hkj.com
[56] https://www.radioid.net
[57] https://www.arednmesh.org
[58] https://openwrt.org

- Automatic network and route discovery,
- Automatic configuration of networking parameters such as IP address assignment, gateway configuration, etc.,
- Seamless interoperability between Ethernet connections, radio connections, and Internet connections (tunneling between AREDN nodes).

What is most impressive about AREDN is the “Automatic network and route discovery” feature. There have been innumerable attempts to implement “open” mesh networking, and mesh networking was even codified into an IEEE standard for Wi-Fi – 802.11s[59]. But all such popular, usable implementations of mesh networking have been proprietary: “Brand X” Wi-Fi and “Brand Y” Wi-Fi will not automatically recognize each other’s mesh network capabilities. AREDN solves that dysfunction: any AREDN devices that are on the same frequency (and same channel size – 5, 10, or 20 MHz) will recognize each other and “just mesh up” regardless of hardware manufacturer or model. This provides a unique capability to Amateur Radio Operators – not only access to some portions of spectrum that are semi-exclusive to Amateur Radio, but the “it just works” capability to local area and wide area high speed microwave networking.

AREDN Networks have been formed in many areas of the US and internationally, and it’s been reported that some Information Technology (IT) professionals have gotten their Amateur Radio licenses specifically to work with Amateur Radio Operators to build out and experiment with AREDN networks.

New Packet Radio (NPR)
Despite the name, New Packet Radio[60] has no overlap with classic Amateur Radio Packet Radio: An NPR unit communicates via Ethernet, uses TCP/IP natively over the air, and communicates at speeds up to 500 kbps using a 100 kHz channel. NPR is Open Source, and can be built for < $100, or assembled and tested units (now in their fifth generation) are available for purchase[61].

NPR is notable that upon its debut in 2019, it was a one-person project by F4FDK and is an example of how much innovation can be done in Amateur Radio. NPR can be used as point-to-point, point-to-multipoint, or in a “repeater” configuration. Although it was originally intended as a “feeder” for high-speed microwave networks such as HAMNET[62] and AREDN, it is fast enough and useful enough to operate as a standalone network. The NPR unit does not generate much RF transmit power, but NPR is designed to be able to use commonly available power amplifiers intended for use with Digital Mobile Radio (DMR) portable radios.

Open IP over VHF / UHF
David Rowe VK5DGR[63] is creating a system he calls Open IP[64] that will do native TCP/IP over VHF / UHF frequencies, at a data rate of up to 100 kbps, at a range up to 15 km (urban). The

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[59] https://en.wikipedia.org/wiki/IEEE_802.11s
[60] https://hackaday.io/project/164092-npr-new-packet-radio
[61] https://elekitsorparts.com/product/npr-70-modem-by-f4hdk-new-packet-radio-over-70cm-band-amateur-radio-packet-radio/
[62] https://hamnet.eu/site/
[63] https://www.rowetel.com
[64] **Part 1** - http://www.rowetel.com/?p=7207, **Part 2** - http://www.rowetel.com/?p=7334, **Part 3** - http://www.rowetel.com/?p=7567, **Part 4** - http://www.rowetel.com/?p=7567, **Part 5** - http://www.rowetel.com/?p=7898.

transmitter is a Raspberry Pi. The receiver is a generic RTL-SDR[65] dongle. This system is *almost entirely software*. It sounds… speculative… but I'm not betting against VK5DGR.

Software Defined Transceivers using Raspberry Pi
RadioBerry[66], TAPR WSPR[67] Boards[68], and most recently, CaribouLite[69] all leverage the abundant compute power and hardware flexibility and the ubiquity[70] of the Raspberry Pi computers[71] to trade hardware development of a standalone radio unit for a simplified design that puts more of the radio function into software and computing power. The TAPR WSPR Boards are notable that they are very simple, acting mostly as a filter to clean up harmonics and other undesirable signals resulting from rapidly toggling an Input / Output pin at high speed to produce a radio signal at HF frequencies. The CaribouLite is notable because it was designed to use the more minimal $15 - $20 Raspberry Pi Zero / Zero 2 instead of the (full size) $35 - $80 Raspberry Pi units.

HAMNET Access Protocol (HNAP)
HNAP[72] is an "precompiled image" for the ADALM-PLUTO[73] Software Defined Transceiver (SDT) for data communications on the Amateur Radio 420-450 MHz band. The "Pluto" is intended for use by students and for evaluation of the vendor's chipsets and is typically used with GNU Radio. In contrast to the complexity of GNU Radio, HNAP is "plug and play" for Amateur Radio data communications. *Amateur Radio needs a lot more of these practical, easy-to-use examples of Software Defined Radio technology.*

Decentralized Amateur Paging Network (DAPNet)
Paging[74] is a radio technology that dates back to the 1950s – broadcasting a signal unique to individual pagers, in continuous sequence. Paging technology evolved from a simple "beepers" to units that could receive text messages, to a few "two-way" paging systems where the pager unit could send back acknowledgement-of-receipt and reply messages. Paging technology has largely been obsoleted by ubiquitous mobile telephony and integrated text messaging.

Paging protocols are a robust method to transmit text messages. DAPNet[75] has adapted text messaging paging technology for Amateur Radio use with low-cost hardware, Open Source software, and multiple Amateur Radio stations via Internet into an *Amateur Radio* paging network.

Repeater Builder Website
There are many unique websites that support Amateur Radio activities, but there are few with the breadth and depth as Repeater Builder (RB)[76]. RB is so extensive I refer to it as an Omnipedia. Not only are there tutorials about how to create an Amateur Radio (or other) repeater, but there is also extensive reference material, including documentation about radios

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65 https://www.rtl-sdr.com/about-rtl-sdr/
66 https://github.com/pa3gsb/Radioberry-2.x/wiki
67 https://physics.princeton.edu/pulsar/k1jt/wspr.html
68 https://tapr.org/product/wspr/
69 https://www.crowdsupply.com/cariboulabs/cariboulite-rpi-hat
70 Until the "chip shortage" beginning in 2020
71 https://www.raspberrypi.com/products/
72 https://hnap.de/about/
73 https://www.analog.com/en/design-center/evaluation-hardware-and-software/evaluation-boards-kits/adalm-pluto.html
74 https://en.wikipedia.org/wiki/Pager
75 https://hampager.de/#/
76 https://www.repeater-builder.com/rbtip/index.html

that are no longer supported by their manufacturer. I'm unaware of the depth of information for topics like this outside of Amateur Radio.

Developing New *Systems*

Some technological innovation in Amateur Radio requires "Thinking Big" by imagining the *whole system*. The systems in this section illustrate technological innovation in Amateur Radio by imagining the big picture.

KA6M-1 Digipeater
Talk about developing new systems and technological innovation in Amateur Radio!!! In late *1980*, years before the phrase Packet Radio would be familiar to Amateur Radio Operators, the KA6M-1 Digipeater[77] began proving out Packet Radio technology in US Amateur Radio, and especially the capability to use of "repeaters" that used only a single frequency by receiving, buffering, and then transmitting the received data – digipeaters.

The KA6M-1 Digipeater used the Packet Radio protocols developed by the Vancouver Digital Communications Group (VADCG)[78] and presaged the development of the TAPR TNC-1[79] and very popular TNC-2 (with built in digipeating capability), and APRS.

Automatic Packet Reporting System (APRS)
Over four decades, APRS[80] has become so ubiquitous within Amateur Radio that it's easy to forget how technologically innovative APRS was when it debuted in early 1980s. Bob Bruninga WB4APR combined a GPS receiver (then, new technology), a Packet Radio TNC, and an Amateur Radio transmitter to transmit real-time position reports via radio. The receiving station was equally simple – an Amateur Radio receiver, a Packet Radio TNC, and a personal computer with map software to display the position data.

APRS is now an entire ecosystem, embedded into radios, a worldwide network of digipeaters, Internet gateways, inexpensive trackers… *ubiquitous*! APRS technology is so ubiquitous that it's being used to track balloon launches that are classroom experiments using unlicensed radio transmitters. It's probably one of the proudest achievements of WB4APR (now a silent keyboard) that APRS is a permanent presence on the radio stations on the International Space Station. APRS continues to evolve, and some in a position of influence within the APRS developer community have taken the first steps to form an "APRS Foundation"[81]. It's worth remembering that the technological innovation of APRS, and Automatic Identification System (AIS)[82] used on vessels, *began within Amateur Radio*.

Winlink
Like APRS, the Winlink[83] system has become so embedded into Amateur Radio over decades that we forget how technologically innovative it was at the time to be able to reliably send Internet email via Amateur Radio, especially via HF from nearly anywhere on Earth. Like APRS, Winlink now works so well, and has done so for so long, it feels like "a utility" within Amateur Radio. Winlink seamlessly provides a network of Internet servers, and Winlink Radio Mail

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77 http://www.pprs.org
78 https://tapr.org/pdf/CNC1986-FeaturesOfVadcgTNCplus-VE7APU.pdf
79 https://web.archive.org/web/20090704021623/http://www.tapr.org/history.html
80 https://en.wikipedia.org/wiki/Automatic_Packet_Reporting_System
81 http://lists.tapr.org/pipermail/aprssig_lists.tapr.org/2022-March/049356.html
82 https://en.wikipedia.org/wiki/Automatic_identification_system
83 https://winlink.org

Servers (RMS) are provided by individual Amateur Radio Operators. Winlink has developed client and RMS software that makes it easy to set up a VHF / UHF RMS, and the Winlink client software is stable and sufficiently well-documented that newcomers are easily able to quickly get up to speed on using Winlink at their own Amateur Radio station. Winlink is another example of technological innovation that *began within Amateur Radio*.

Terrestrial Amateur Radio Packet Network (TARPN)
TARPN[84] has re-thought, and re-engineered Amateur Radio Packet Radio networking, identifying weak points in “traditional” packet radio networking and architected TARPN networks to eliminate those weaknesses. For example, for best performance, TAPRN networks do not use Packet Radio Digipeaters[85].

TAPRN uses Amateur Radio networking software written to run on Raspberry Pi Linux and provides copious documentation and a Raspberry Pi image to make it easier to get a TARPN network up and running.

Out of this work, TARPN has created its own hardware: the NinoTNC[86] - a KISS[87] TNC[88] connected via USB and providing 1200 / 2400 / 4800 / 9600 bps data speeds. This unit has gone through a number of evolutions as TARPN has gathered more feedback about its performance in the real world, and feedback on building the unit (it’s supplied as a printed circuit board, a programmed processor, and a list of parts that the user procures).

Perhaps more notable than the NinoTNC was the parallel development of a *new Forward Error Correction (FEC)[89] mode* called Improved Layer 2 Protocol (IL2P)[90]. IL2P is an efficient protocol because it does not attempt backwards compatibility with AX.25. Interoperability between AX.25 and IL2P isn’t an issue with TARPN networks as all connections are point-to-point, thus AX.25 vs IL2P need only be negotiated between each two endpoints. IL2P was sufficiently well documented that IL2P support has been designed into Dire Wolf Software TNC (see below).

File Distribution via Broadcast - flamp and RadioMirror
Phil Karn KA9Q once stated (paraphrased) “Why do we in Amateur Radio try implement one-to-one communications via radio instead of taking advantage, as much as possible, of *the broadcast nature of radio?*”. flamp[91] and RadioMirror[92] are two implementations of that observation that radio communications are inherently a broadcast medium, from one transmitter to any number of receivers within range of the transmitter. With these systems, at the transmitter, each file to be distributed is broken into blocks and given a checksum and sequence number, and all blocks / files are transmitted in turn. When all blocks / files have been transmitted, the process repeats. Any new or changed files are added to the queue.

At the receiver, each block is received, and the checksum verified. Valid blocks are queued for assembly per the sequence number. Once all blocks are received correctly, the file is written. If

84 http://tarpn.net/t/packet_radio_networking.html
85 http://www.aprs.net.au/vhf/aprs-digipeaters-101/
86 http://tarpn.net/t/nino-tnc/nino-tnc.html
87 https://en.wikipedia.org/wiki/KISS_(TNC)
88 https://en.wikipedia.org/wiki/Terminal_node_controller
89 https://en.wikipedia.org/wiki/Error_correction_code#Forward_error_correction
90 http://tarpn.net/t/il2p/il2p.html
91 http://www.w1hkj.com/files/manuals/US_English/FLAmp_2.2_Users_Manual.pdf
92 https://www.superpacket.org/2021/03/revisiting-radiomirror.html

a block is missing (discarded because the checksum failed), assembly of that file waits until the next cycle.

The benefit of file distribution via broadcast is that there is no need for a two-way handshake such as a packet radio file transfer. The process can be a background task for populating files that require periodic updating, such as map files, lists of repeaters, and even Amateur Radio bulletin texts. In 2022, the receiver can be simplified to an inexpensive Software Defined Receiver dongle and a Raspberry Pi.

Innovative Use of Inexpensive Computing Power

These projects illustrate technological innovation in Amateur Radio by imagining "what *could* we do to create better radio technology by making use of inexpensive computing power?". It should be noted that the ubiquity and versatility of the Linux operating system is usually a "silent partner" with inexpensive computing power to enable many technological innovations in Amateur Radio.

WSJT-X
WSJT-X[93] illustrates (humorously) the "dangers of a Nobel Prize laureate with too much time on his hands". After retiring from a distinguished career as an Astrophysicist, Joe Taylor K1JT[94] applied his extensive knowledge of radio signal processing technology to Amateur Radio weak signal modes. The various WSJT-X modes utilize computing power to apply both forward error correction and "deep down in the noise signal recovery" to provide new capabilities to Amateur Radio using very, very low power, including Earth Moon Earth (EME)[95] communications with modest Amateur Radio stations, meteor burst[96] (meteor scatter) communications, and more. Other WSJT-X modes provide communications when other modes cannot operate due to low signal level or excessive channel noise.

Dire Wolf Software TNC
Dire Wolf[97] (ostensibly) is an acronym for "Decoded Information from Radio Emissions for Windows Or Linux Fans". Dire Wolf is a software implementation of an Amateur Packet Radio Terminal Node Controller (TNC) and is an actively maintained Open Source software project.

In developing Dire Wolf, John Langner WB2OSZ applied a key insight, that AX.25 packet radio required retransmission of an entire packet if even 1 bit was incorrect and thus the packet's Cyclic Redundancy Check (CRC) failed. WB2OSZ wondered "what if we flip each individual bit, and see if the CRC is correct? There is ample computing power available for such a test, and that simple innovation resulted in decoding many more packets successfully. Of course, there were cases where the bit flipping resulted in an incorrect packet (despite the CRC), so he applied other techniques to ensure that the "bit flipping" resulted in a correct packet.

Dire Wolf has evolved to be a "Packet Radio toolkit" – it can act as an APRS digipeater, an APRS Igate[98], a high speed TNC (9600 bps, and many other data speeds other than 1200 bps), and many other capabilities. Dire Wolf works very well on a Raspberry Pi computer.

93 https://physics.princeton.edu/pulsar/k1jt/wsjtx.html
94 https://en.wikipedia.org/wiki/Joseph_Hooton_Taylor_Jr.
95 https://en.wikipedia.org/wiki/Earth–Moon–Earth_communication
96 https://en.wikipedia.org/wiki/Meteor_burst_communications
97 https://github.com/wb2osz/direwolf
98 http://www.aprs-is.net/igating.aspx

It's notable that Dire Wolf has implemented two Forward Error Correction systems for Amateur Radio Packet Radio – FX.25[99], which is compatible and interoperable with conventional AX.25[100] (in the stable distribution of Dire Wolf) and Improved Layer 2 Protocol (IL2P) developed for the NinoTNC (in the development branch of Dire Wolf).

VARA FM

VARA[101] is a robust and fast audio interface ("sound card") data mode for reliable file transfers. VARA is most typically used by Winlink user stations and Winlink Remote Mail Servers (RMS) for faster and more reliable file transfers than previous methods such as WINMOR and packet radio.

VARA is not compatible with any other data communications mode (such as packet radio); VARA stations can only communicate with other VARA stations. VARA FM is designed for use on the wide, quiet channels of Amateur Radio VHF / UHF, achieving speeds up to 25 kbps and incorporating Forward Error Correction (FEC) for very fast and reliable file / message transfers compared to conventional packet radio, even at 9600 bps.

VARA achieves its robustness and speed by incorporating a number of techniques:

- Orthogonal Frequency Division Multiplexing (OFDM) generates multiple subcarriers within the audio signal.
- Varying modulation methods (Modulation Index) – FSK through 256 QAM depending on mode and quality of channel between stations.
- Robust handshake between transmitting and receiving station to negotiate best possible speed on each transmission.
- Huffman data compression.
- Turbo Codes Forward Error Correction.

While VARA FM achieves its best performance using radios that provide "flat audio" connections (bypass pre-emphasis and de-emphasis audio circuits), it's quite usable when connected to speaker and microphone connections, even on portable radios. Most notably, VARA FM will "handshake" when establishing a connection and negotiate the best possible common speed between two VARA stations, overcoming the issue with packet radio 1200 bps and 9600 bps stations not being able to communicate with each other.

ka9q-radio

ka9q-radio[102] virtualizes a single Software Defined Receiver into multiple receiver modules. "A single Raspberry Pi 4 can simultaneously demodulate, in real time, every narrowband FM channel on a VHF / UHF band (i.e., several hundred) with plenty of real time left over." The use of IP multicasting[103] "makes it easy for more than one module, on the same computer or on a LAN, to operate on the outputs of other modules…".

Codec 2 – Open Source / non-proprietary Digital Voice

The work on Codec 2[104] began more than a decade ago. Early in the experiments with the use

[99] https://en.wikipedia.org/wiki/FX.25_Forward_Error_Correction
[100] https://en.wikipedia.org/wiki/AX.25
[101] https://rosmodem.wordpress.com
[102] https://github.com/ka9q/ka9q-radio
[103] https://en.wikipedia.org/wiki/IP_multicast
[104] https://en.wikipedia.org/wiki/Codec_2

of digital voice in Amateur Radio, a study concluded that there was no practical method of implementing digital voice in Amateur Radio that wouldn't infringe on the numerous digital voice patents at the beginning of conversion of cellular phones from analog voice to digital voice.

In the development of Codec 2, an interesting approach was used: instead of trying to work around patented digital voice methods, patented methods of digital voice *where the patent had expired* were sought out. Codec 2 is the result, a fully Open Source software approach to digital voice that is finally beginning to see widespread use now that it can be applied as "just a bit more software" to Software Defined Radio transceivers. Codec 2 is the digital voice implementation used in M17 Project.

Codec 2 / FreeDV Data for HF
Having been proven robust and spectrally efficient for use on HF, the technology and modems developed for Codec 2 / FreeDV[105] are being adapted as "transport" for text messaging and data over HF in two separate projects – Codec 2 HF Data Modes (Part 1)[106] (Part 2)[107], and FreeDATA[108].

Multi-Mode Digital Voice Modem (MMDVM)
Sometimes talented Amateur Radio Operators see a "problem" as a challenge and take a unique approach to solving the challenge. The genesis of MMDVM[109] developed by Jonathan Naylor G4KLX, was the proliferation of digital voice implementations in Amateur Radio that weren't interoperable:

- D-Star
- Digital Mobile Radio (DMR)
- Next Generation Digital Narrowband (NXDN)[110]
- Project 25 (P25)[111]
- System Fusion[112]

Thus, the MMDVM which handles "all of the above" on an equal basis. MMDVM can also be used to "transcode" one digital voice mode to another, such as linking a D-Star repeater to a DMR repeater. MMDVM can be used to build repeaters which work equally well on all digital voice modes, as well as the basis of "personal hotspots" which can act as "Pico repeaters" for very localized use. Other modes have been added to MMDVM including FM, Packet Radio (AX.25), POCSAG[113] (paging), and M17.

105 https://freedv.org
106 http://www.rowetel.com/?p=7167
107 http://www.rowetel.com/?p=7665
108 https://groups.io/g/freedata
109 https://github.com/g4klx/MMDVM
110 https://en.wikipedia.org/wiki/NXDN
111 https://en.wikipedia.org/wiki/Project_25
112 http://systemfusion.yaesu.com/what-is-system-fusion/
113 https://en.wikipedia.org/wiki/Radio-paging_code_No._1

One Last Vignette – FlexRadio Systems Origins in Amateur Radio

The crossovers from Amateur Radio to government and industry are innumerable. That point is made very well in a film[114] made during World War II about the Hallicrafters SCR-299. This unit was designed and manufactured for Amateur Radio Operators, but during World War II it was adapted for mobile use on the battlefield.

This "crossover" continues to the present day, as exemplified by the emergence of FlexRadio Systems.

FlexRadio Systems[115] began as a personal project by Gerald Youngblood K5SDR in 2013. K5SDR's goals were to familiarize himself with (then) new (to Amateur Radio) technology of Digital Signal Processing. He published[116] [117] [118] [119] his project, the SDR-1000, in QEX magazine[120] and it was well-received to the point that K5SDR was asked to provide kits of parts to allow other Amateur Radio Operators to build their own SDR-1000s. On the basis of that kit, FlexRadio Systems was founded in K5SDR's home[121]. FlexRadio quickly outgrew those modest beginnings and FlexRadio's innovative and extremely cost-effective Software Defined Radio technology quickly gained notice in government and industry that needed highly flexible and cost-effective radio systems, which FlexRadio grew rapidly to accommodate.

In March 2022, FlexRadio was awarded a significant government contract[122] to supply radio systems to US Air Force aircraft. Despite the inevitable motivation to change its focus to more lucrative government and industry products, FlexRadio has chosen[123] to remain grounded in Amateur Radio and continue to develop new products for Amateur Radio:

Throughout the [US Government] project, FlexRadio has been asked about our ongoing business and we have continued to inform all of our customers that the Amateur Radio business is strategic for both FlexRadio as well as the long-term benefits to the radio art and communications community. Specifically, FlexRadio has repeatedly asserted that we believe that continuing to invest in Amateur Radio is an investment in the future of communications. There is not a corner of the communications world that FlexRadio has been involved in that we do not see Amateurs making key contributions.

FlexRadio Systems, the new USAF radio, and the stellar example to other Amateur Radio manufacturers in the overwhelming advantages of a *fully Software Defined* radio architecture, *would not have come into existence without Amateur Radio*.

[114] https://www.youtube.com/watch?v=A6z18otFPVY
[115] https://www.flexradio.com
[116] http://www.arrl.org/files/file/Technology/tis/info/pdf/020708qex013.pdf
[117] http://www.arrl.org/files/file/Technology/tis/info/pdf/020910qex010.pdf
[118] http://www.arrl.org/files/file/Technology/tis/info/pdf/021112qex027.pdf
[119] http://www.arrl.org/files/file/Technology/tis/info/pdf/030304qex020.pdf
[120] http://www.arrl.org/qex
[121] https://www.flexradio.com/videos/flexradio-history-with-gerald-youngblood/
[122] https://www.flexradio.com/insider/press-releases/flexradio-awarded-contract-in-collaboration-with-bae-systems/
[123] https://zeroretries.substack.com/i/43856023/flexradios-commitment-to-amateur-radio

Conclusion

In “About Zero Retries”[124] (a link that appears near the beginning of every issue), I list a number of poignant quotes. These three seem particularly relevant to mention in this paper:

- Ultimately, amateur radio must prove that it is useful for society - Dr. Karl Meinzer DJ4ZC.
- The Universal Purpose of Ham Radio is to have fun messing around with radios - Bob Witte K0NR.
- Amateur Radio is literally a license to experiment with radio technology! - Steve Stroh N8GNJ

I agree with DJ4ZC – it is imperative that Amateur Radio “prove its worth”.

I also agree with K0NR – much of Amateur Radio is, in the end, having fun with radios.

The last quote, mine, is a fact that is almost completely overlooked – Amateur Radio is… (quite literally) a *license*… to *experiment*… with *radio technology*!

I hope that this paper has helped to illustrate that there *is* an *amazing* amount of technological innovation occurring *now* within Amateur Radio. The scale and scope of that technological innovation isn’t widely recognized in part because of the highly decentralized… and individualistic nature of Amateur Radio and Amateur Radio Operators.

Another part of that lack of recognition is that technological innovation in Amateur Radio isn’t regularly featured in Amateur Radio “media” such as popular magazines, YouTube shows, podcasts, and blogs. It’s no wonder that the popular perception of Amateur Radio is often “old… tired… no longer relevant”. Amateur Radio *really* needs to *change* that perception… *somehow*.

It is critical that the technological innovation occurring now, and in projects, and products, and systems that will extend into future years, and even decades be recognized by the public, but more importantly by industry, regulators, and lawmakers. In my opinion, such wider recognition of technological innovation in Amateur Radio will be a primary justification for Amateur Radio (and its operations in various portions of spectrum) being allowed to continue.

The vignettes of technological innovation mentioned in this paper were selected from a much larger collection of such information on a web page:

Zero Retries 0070 Omnibus of Zero Retries Interesting Information

https://www.superpacket.org/zero-retries-0070-omnibus.html

If you would like to read more about technological innovation in Amateur Radio, subscribe to the Zero Retries Newsletter. It is free (as in beer) and delivered weekly via email. Join the fun at https://zeroretries.substack.com (eventually migrating to https://zeroretries.org).

Steve Stroh N8GNJ
September 2022

[124] https://zeroretries.substack.com/about