D-STAR, Part 1 of 3:

New Modes for VHF/UHF Amateur Radio

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D-STAR: New Modes for VHF/UHF Amateur Radio, Part 1

Our friends in JARL have created a new digital communication standard. Let's look at their new system, and what's in it for hams.

By John Gibbs, KC7YXD

This article is the first in a three-part series describing and analyzing a new communication standard developed by the Japan Amateur Radio League (JARL). The first part focuses on the advantages of upgrading our VHF/UHF equipment to a new, more capable system. The second article in the series addresses the technical design considerations of a digital voice and high-speed data system in the VHF/UHF spectrum. The third, and final, article discusses the D-STAR standard and how it addresses the needs and technical issues raised in the two previous parts.

JARL has developed a new open standard for VHF/UHF digital radio called D-STAR. The system supports both digitally modulated voice transmission and data transmission, including Internet connections, at DSL rates.

At a time when the third-generation (3G) cell phone proposals for high-speed data have been severely delayed, D-STAR presents Amateur Radio operators with the opportunity to bring the Internet Age to mobile and portable operation.

I have been fortunate to be one of the first hams to see and use the prototype transceivers of this new Amateur communication system. Therefore, I would like to take this opportunity to share some of the knowledge and experience I have gained. In this article, I will present the objectives of the new JARL D-STAR system and provide a glimpse of the capabilities of this new system and the engineering tradeoffs that went into the system design. I hope you will find it interesting both in developing an understanding of this system and as an insight into the design process of a digital radio system.

One of the major goals of D-STAR is that it be an open system. This series of articles contains enough system details for a skilled ham to develop a homebrew D-STAR digital voice transceiver.[1]

If you are interested in this system, you may soon have a chance to try it yourself. Because the FCC encourages the Amateur Radio community to develop new digital modes, the US has the regulatory structure in place for hams to use an all-digital voice and high-speed data radio system without special licensing or permits. US hams will therefore be the first in the world with the opportunity to use the new D-STAR system illustrated in Fig 1.

Regular readers of *QEX* know that hams have been experimenting with digital voice.[2] In the US, the FCC encourages hams to continue such experimentation to demonstrate our stewardship of our spectrum. In addition to individual efforts, Amateur Radio organizations have also been promoting digital radio. For years, TAPR has focused exclusively on advancing the state of the art in Amateur Radio digital communications. The ARRL has increased its efforts in this area by sponsoring the establishment of Technology Task Force Working Groups on digital voice, high-speed multimedia and software radio.

In addition to the efforts of individual hams and their organizations, one manufacturer has already introduced a digital voice option to handheld VHF/UHF radios. Unfortunately, these

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[1]Notes appear on page 34.

radios are of limited usefulness because the necessary repeater infrastructure for VHF/UHF digital voice operations with these radios does not exist. These radios will not work through existing analog repeaters and the necessary digital repeaters have not been developed. Early on in the D-STAR planning, the JARL recognized that developing VHF/UHF digital capabilities also requires developing new standards for digital voice repeaters and the links between repeaters.

D-STAR History

The D-STAR standard not only addresses the needs of VHF/UHF voice and data communications with mobile and handheld radios, but also provides the standards for repeater-to-repeater linking and Internet access. It was clear that developing and testing such a complex system would take many man-years of engineering and testing. The efforts that would be required to achieve this in a timely manner would far exceed any reasonable expectations of volunteer ham labor, no matter how dedicated. So, the JARL contracted with the Amateur Radio manufacturer ICOM to develop and evaluate D-STAR prototype hardware. D-STAR has been under development since 1998 and the system operation has been proven in lab and field tests. The result of all this development effort is about to bear fruit. The JARL expects to finalize the D-STAR standard this summer.

A D-STAR mobile transceiver called the ICOM ID-1 was used for field trials in the Tokyo area (see the cover photo on this issue) and shown at three US Amateur Radio shows: Dayton Hamvention 2002 and 2003 and the Digital Communication Conference (DCC) in Denver last fall. Since then, repeaters and microwave links have been developed and are currently available on a limited basis to application developers in the US. All these D-STAR compatible components will soon be shipping in quantity, and we expect that other manufacturers will be shipping D-STAR-compatible radios in the future.

Existing VHF/UHF System Properties

To replace any existing system with a new standard, there must be compelling reasons for incurring the expense of new equipment. So it is good to start the discussion of D-STAR with a look at the capabilities and limitations of our existing VHF/UHF Amateur communication systems in Tables 1 and 2. To do this, let us look at the capabilities of a representative voice repeater system that covers the Pacific Northwest and beyond: the Evergreen Intertie.

The Evergreen Intertie connects more than 23 repeaters by full-duplex UHF radio links that are transparent to the user. From my location, there are two main links in the system, a North-South link that connects Western Washington and Oregon and an East-West link that crosses the Cascade Mountains and connects to cities in Eastern Washington.

Users can control switches using DTMF tones to connect repeaters to the link. The way this particular system is configured, a minimum of three switches must be set by a user or control operator to connect two repeaters. In a more-extreme case, seven switches must be set to talk from Seattle repeater K7NWS to Portland repeater KJ7IY. Of course, each switch that connects to the next link may be already in use, so it can be difficult for a user to establish such links if the system is heavily used.

On a repeater link, only one contact can be held on a link at a time. That is, unlike the telephone system, there is no multiplexing on links. If a link is in use or out of service, there is no way to link the repeaters unless an alternate path is available.

Another difference from the telephone trunk system lies in how a link is established. In the telephone system, the system automatically picks the link based on the call destination and the trunk lines currently available. In the Evergreen Intertie, the user must determine the logical path through the repeater links and to know the DTMF codes for each of the switches.

Amateur Radio packet systems offer an analogous set of features through dedicated packet nodes (simplex repeaters.) Packet radio is used to transfer data (for example, computer files) and for keyboard contacts. It might even be possible to have a digital voice contact on a 9600-bps system. However, the system is packet-oriented, which means that real-time communications are not guaranteed. Unless the system was very lightly loaded, some of the voice packets would be unacceptably delayed.

Both the amateur voice repeaters and packet nodes are FM systems. Within the limitations of the existing analog FM technology, some very creative communication solutions have been developed. For instance, sub-audible tone codes are used to protect repeaters against accidental activation by interference. DTMF is used to control some repeater functions, activate a phone patch or for selective calling of amateurs.

Enterprising hams continually add new capabilities to the systems. A few

Table 1—Existing VHF/UHF Amateur Radio System Features

- Voice is FM, half duplex
- Data is FSK, simplex
- CTCSS protection
- DTMF control
- Linked repeaters
- 1200/9600 packet
- APRS
- Voice over Internet

Table 2—Existing VHF/UHF Amateur Radio System Limitations

- Spectrally inefficient
- Low speed data
- One QSO per link
- Difficult to establish links
- Cannot mix data and voice

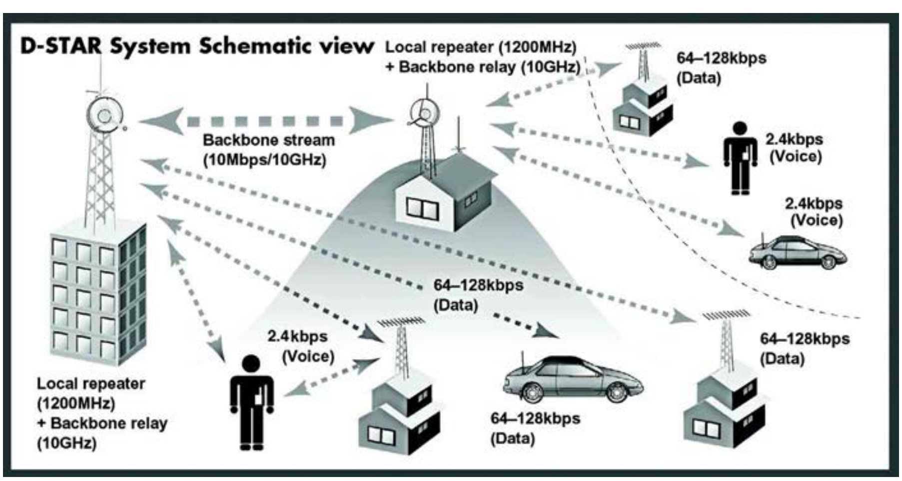

Fig 1—JARL's proposed D-STAR system offers digital voice and data communication on 1.2-GHz with repeaters linked on 10 GHz and Internet gateways.

examples that come to mind include satellite gateways, GPS-based location systems (APRS) and worldwide communications with VHF/UHF transceivers when voice-over-Internet-protocol (VOIP) is added to a repeater. Yet we are rapidly approaching the limit of what we can do with the existing infrastructure, as we can see by investigating the limitations of existing VHF/UHF Amateur Radio systems (see Table 2).

Spectral Efficiency

The first major limitation is spectral efficiency. The amateur community's VHF/UHF spectrum usage has not changed despite dramatic improvements in communication technology that have occurred in the last few years. The FCC views the radio spectrum as a finite resource that must be efficiently shared among many users. There are many new potential users appearing for the VHF/UHF spectrum, and they are often looking at the spectrum that has been allocated for Amateur Radio. A growing part of ARRL resources are being devoted to spectrum-defense.

However, defending our usage of these valuable frequencies will become more difficult because the current amateur FM system is not spectrally efficient. Today, the FCC only grants new licenses in Land Mobile services to users that meet reduced spectrum-occupancy requirements. The FCC calls this "refarming." The FCC has extended this principle to other radio services. For example, the existing GMRS spectrum was refarmed with FRS channels placed between the old GMRS channels. There is no reason why we should feel that the Amateur Radio Service would be exempt from the requirement for spectral efficiency.

As a matter of fact, the quest for spectral efficiency is increasing. Current Land Mobile services refarming is from 25-kHz channel spacing to 12.5 kHz. However, in the next few years, the FCC plans to repeat this process and force all new Land Mobile Service licenses to use equipment compatible with 6.25-kHz channel spacing. It is not clear that FM radios can be developed that will meet the stability and bandwidth requirements of such a system and be sold at an affordable price, so radios using other technologies may need to be developed. But what is certain from modulation theory is that as the deviation is reduced, the signal quality advantage of FM over AM systems (including SSB) quickly disappears.

Data Rate

A second limitation is the 9600-baud rate limitations of existing commercially available radios. In this data-intensive Internet age, this speed is woefully inadequate. Any new system should have the capability of supporting data transfers at speeds rivaling DSL.

Limited Linking

As mentioned above in the Evergreen Intertie example, a severe limitation of the current FM-analog repeater system is the number of contacts that can be handled by a link. An ideal repeater-to-repeater link would have much wider bandwidth than the existing links. This bandwidth would then be dynamically allocated between voice contacts and high-speed data users.

In addition, as we have seen, it is difficult for the user to establish links between repeaters. With today's low-cost computing power, a more automated method of calling a distant ham could certainly be developed.

Data and Voice

The final and very significant limitation of the existing systems is that repeaters can only handle voice or data, not both simultaneously. As we shall see later, there are many applications that could be opened to Amateur Radio operators if this feature could be incorporated in a new VHF/UHF system.

Desired Properties

Having considered the features and limitations of current analog FM systems, let us next consider what properties any new analog or digital systems should have. Ideally, any new system should solve the limitations of the existing systems without losing any of the features. In addition, any new system should have the properties described below and in Table 3.

Table 3—Desired Properties of New VHF/UHF Amateur System

- Compatible with regulations
- Worldwide standard
- Enables new applications
- Enhancement friendly
- Scalable
- Open standard
- Repeater operation
- Linking repeaters
- Simplex
- High speed data
- ANI
- Expandable
- Affordable

Compatible with Regulations

If a new system required changes in the FCC regulations, it might take years before it could be adopted. Fortunately, this is not necessary for digital voice and data transmissions in the US.

The FCC encourages the Amateur Radio community to develop digital voice and new digital data communication systems. One example is the FCC's attitude toward the new HF digital modes such as PSK31. There was some concern in the amateur community that the encoding used in PSK31, called Varicode, would be considered a form of encryption and hence barred by the Part 97 regulations. However, the FCC has clearly and repeatedly stated that encoding is not encryption and that as long as the encoding method is public there is no regulatory problem.

Where should digital voice transmissions occur in the current band plan? Again the FCC in its encouragement of digital radio has already decided that digital voice operations belong in the phone bands.[3]

What regulatory issues are there for new linked systems? William Cross, W3TN, of the FCC Policy and Rules Branch, made it clear at his presentation at Dayton last year that there are no rules specifically written for linked systems; the FCC regulates stations, not systems.

Finally, emergency operation is clearly one of the requirements for any Amateur Radio system to meet one of the Part 97 justifications for the Amateur Radio Service. Any new system must not only be available to support communication needs during an area-wide emergency, but an amateur must be able to break in and use the system during an accident or other local emergency.

A Worldwide Standard

Why is it desirable to be compatible with an international standard? The primary reason for all countries to share the same system architecture is to make the radios affordable. If the radios and the repeater infrastructure are not within the financial reach of the majority of the ham community, no amount of extra features will make a new system successful.

Radio costs are dramatically dependent on sales volume both because research and development costs can be spread over a larger number of radios and because manufacturing unit costs decrease as volume increases. Today North America accounts for about a third of the world's Amateur Radio licenses. Japan, with a far smaller population, has about another third. So if

Japan and the US agree on a single standard, the manufacturing volume could double, which would dramatically reduce radio costs for all amateurs. If the rest of the world also joined in the standard, further cost reductions would follow. As an example of what can happen when there is not a world standard, consider the 222-MHz band.

Because the band is not available worldwide, manufacturers offer a limited number of transceiver models. And we find that equivalent rigs (if even available) tend to be more expensive than the high-volume 2-meter rigs.

A second reason for a worldwide standard is that tying repeaters together via the Internet is becoming a popular feature of today's repeater systems. Any new system must support this trend for both voice and high-speed data. This could be done by specifying a protocol that two otherwise incompatible systems would use to exchange data; but due to the economic issues discussed above, this is a less-than-ideal solution.

New Applications and Enhancements

To take full advantage of the digital revolution in Amateur Radio, minimum standards will need to be established. Unlike a telecom system, which needs rigid standardization, an Amateur Radio system must have just enough standardization to allow communication, without inhibiting innovation.[4] This is a difficult balance and requires a great deal of work during the system design to properly blend these conflicting requirements.

Ideally, any new communication system would be a perfect "wireless cable." Of course, one of the things of interest to *QEX* readers is that no communication system is perfect. The study of the impairments and experimenting with ways to improve communications over an impaired channel are interesting areas of our hobby. Every system involves a great deal of compromise; that is a part of daily life for the communication-system design engineer. An ideal system for Amateur Radio would allow a great deal of experimentation that could be layered on top of a well-functioning, but not overly constraining, radio system.

A Scalable System

A cell-phone system will not work until the complete infrastructure is deployed in an area. Clearly this is not practical for Amateur Radio. Any new Amateur Radio VHF/UHF system must be able to work with only one repeater and even—within the limits of line-of-sight propagation—without repeaters at all. Multiple repeaters and the linking of repeaters can come later as the user base develops or as funds become available.

In addition, it is important to be able to communicate with other hams who have not upgraded to the new system. This can be done in two ways: The radios themselves could have analog FM capability, or the repeater can be capable of interfacing with the existing analog radio repeaters.

The system should also be scalable to facilitate emergency operation. Natural or man-made disasters can destroy both the commercial and amateur communication infrastructure. A new communication system should be able to work immediately without repeaters and be flexible enough so that spare transceivers can be connected to quickly form an emergency, temporary repeater.

An Open Standard

As this is an Amateur Radio system, the system should be available from more than one manufacturer. It is desirable to have competition between the radio manufacturers to keep prices low and encourage innovation within the framework of a new standard.

Yet it is at least as important to those of us with *QEX* leanings that the system technology is such that a ham with a sufficient technical background can make any part of the system, including radios, repeaters and repeater links. Because so much of leading-edge communication technology is the intellectual property (IP) of communication companies, the requirement that hams be able to develop and publicize equipment without violating patent rights becomes a system-design challenge.

Further Requirements

High-Speed Data

Fixed site-to-site data links at greater than 9600 bits/s are rare, but not unknown in Amateur Radio. Any new VHF/UHF system should support high-speed data, not only for these fixed links but also for mobile and portable operation. This means the system must tolerate channel impairments like multipath and Doppler shift.

To be able to interface into the vast array of low-cost hardware and software available today, the new VHF/UHF system should appear as a "wireless Ethernet cable" to a PC. You should be able to use any software that can interface with the IEEE 802.3 (10Base-T) Ethernet, connect a cable from the PC to the transceiver and use the computer just as if it was a wired connection. For example, if the other half of the RF link is connected to an ISP, then an Internet browser will work seamlessly and the Amateur world will have high-speed wireless Internet connections.

Repeater Operation

Because the FCC requires that the control operator is able to shut down the repeater and repeaters are often in remote locations, remote control of the repeater must be designed into any new system. With today's systems, shutting down the system is the only option available if a user abuses the repeater. A new system should have the ability to block offenders from repeater access while still allowing others to access the system.

Control over landlines is certainly required, but radio control operation is necessary for those sites without phone-line access. Of course, it is highly desirable that the control operator can use the data capabilities of the system to monitor the status of the system and control many other features.

Linking Repeaters

Any new Amateur Radio system must have a wide-bandwidth links capable of supporting multiplexed contacts. Multiple contacts are necessary because the system should support multiple repeaters at a single site as well as different pairs of sites using the link at the same time. The link must also support both voice and data so that we do not have to invest in two links. The best way to meet this need is for the link itself to be digital and the voice digitized for transmission over the link. Because more than one pair of repeaters is using the link at a time (multiplexed), the link must be full duplex.

Each site in the system repeats the high-speed link signal and extracts and adds the contacts that are appropriate for its site. Normally only one repeater in the system would broadcast the contact. The other repeaters ignore contacts that are not directed to them. Otherwise one contact would tie up the entire repeater system.

Most often, these repeater links would be microwave links. However, because of the distances involved, it may be more attractive to use Internet linking with some repeater systems. Any new VHF/UHF Amateur system should support both types of links.

Simplex

Any new system, no matter what benefits are available from repeater operation, must be able to work simplex without a repeater. And unlike typical fixed digital radio networks, it is critical that anyone tuning the bands can immediately listen in on a contact.

This requires two properties that are not available on many digital radio systems. First, the digital voice system must work without handshakes. That way it is possible to have one talker and many listeners. Second, it must not be necessary to wait for the start of a new transmission to acquire the carrier, frame and bit synchronization necessary to demodulate the contact.

Automatic Number Identification (ANI)

Any new Amateur system should support a higher level of automation in establishing a contact. An equivalent feature to what the commercial Land Mobile market calls "Automatic Number Identification" (ANI) needs to be developed. With this feature enabled, your radio opens squelch only when your call sign is received. Some hams do this today with a DTMF code rather than their call sign, but DTMF codes are not unique and DTMF signaling is very slow. If desired, the radio can beep when you are called or in mobile applications, the horn can sound.

This call-sign squelching principle should also be extended to repeaters. Repeaters today use CTCSS tones to keep from being opened accidentally by interfering signals. On any new system, you should use the repeater call sign to unambiguously and easily open the repeater. This would be followed by the call signs of the party you are calling and the repeater they use so that the system can route your call.

Affordabilty

The system must be designed to be tolerant of the performance limitations of reasonably priced components. Particularly with high-speed data at UHF, the frequency and time accuracy requirements of many modern digital radio systems are so great as to be prohibitively expensive for amateur usage.

Another reason for designing the system to be reasonably tolerant of component and system variations is to allow enterprising Amateurs the opportunity to homebrew their own D-STAR hardware.

Also to save user cost, the system should not be designed for full duplex operation. Full-duplex operation requires expensive isolation between the transmitter and the receiver. Half-duplex and simplex operations allow the sharing of many expensive components between the receiver and transmitter. Finally, radio amateurs almost always operate in these low-cost modes so there is no problem with conversion to new modes.

Advantages of Digital Modulation

In the next part of this series, we delve into the engineering design considerations that were made in developing D-STAR and the technical details of its implementation. Yet, let us conclude by investigating the advantages of a new system based on digital instead of analog modulation.

The first advantage of digital modulation is the ability to reduce occupied spectrum. To meet the regulatory pressures discussed above and to reduce the congestion on our bands, any new system must be spectrally efficient. One solution would be to stay with an analog FM system and reduce the deviation, as the FCC has required of the Land Mobile Service. However, doing so reduces the audio quality that is the major benefit of FM.

It is a better solution to change the modulation completely and transmit voice using digital modulation. However, without careful system design, switching to digital voice could actually increase the bandwidth required for voice communication because of the high bit rates required by uncom-pressed voice. For instance, pulse-code modulation (PCM), as used by the US telephone standard, requires a digital stream of 64,000 bits/s. Even with very elaborate modulation schemes, that high bit rate would require a much wider bandwidth than current FM voice radios.

The enabling technology for digital voice is digital signal processing (DSP). It has long been realized that the information in a voice signal is highly redundant and that it should be possible to establish good transmissions without sending the redundant information. Modern high-speed, low-cost signal processors and very clever algorithms can dramatically reduce the bit rate required to accurately reproduce a human voice in real time. We shall see that it is possible to get similar voice quality at only 2400 bits/s and therefore occupy far less spectrum than today's FM systems.

A second advantage of digital modulation is improved quality. With wide-band systems like HDTV and high-speed wireless Internet service, the most important advantage of digitizing transmissions is the ability to use DSP to correct for transmission errors. This results in improved performance over the vast majority of the operating area. In analog radio communication systems we have little choice but to live with the errors caused by propagation, noise and interference (both natural and man-made). We can sometimes increase the received signal-to-noise ratio by increasing transmitter power and/or using gain antennas. However the fading caused by multipath propagation is not improved by increasing the transmitted signal power. Particularly in mobile wide-band systems, multipath can be a serious problem. You have probably heard multipath impairment if you listen to FM broadcasts in your car. It is perhaps most noticeable if you are at a stop light and hear distortion but move a few feet and the distortion disappears.

But perhaps the greatest advantages of digital voice transmission are the added features that are possible when a digital data payload is added to a voice contact. The availability of simultaneous low-speed data transmission with voice transmissions opens up a whole world of new possibilities for Amateur Radio. Imagine sending still pictures, maps, small data files and GPS position *while* rag chewing. What would it be like to have "instant messaging" on your radio? What a great way to politely break into a contact!

Notes

[1]Remember, however, the D-STAR specifications discussed in this article have not yet been finalized.

[2]See for example "Practical HF Digital Voice," by Charles Brain, G4GUO, and Andy Talbot, G4JNT, *QEX* May/June 2000, pp 3-8.

[3]See, for instance, the editors preface and Paul Rinaldo's, W4RI, comments in a sidebar in "Practical HF Digital Voice," pp 3 and 4.

[4]See "Technical Standards in Amateur Radio," Doug Smith, KF6DX, *QEX* Mar/Apr 2003, p 2.

An Extra class license holder, John usually is found on the HF bands, primarily operating PSK31. At age 3, John exhibited early talents in electronics by "helping" his dad fix a TV. He plugged the speaker into a wall socket! Despite this traumatic start, he spent his youth building Heathkit and Eico equipment, repairing vacuum-tube radios and TVs and designing and building numerous homebrew projects including a Morse decoder high-school project built with resistor-transistor logic in the mid 1960s.

With BSE and MSEE degrees in control and communication theory, he has worked for Hewlett-Packard in the fields of spectrum and network analysis and frequency synthesis. He is currently the research department engineering manager at ICOM America, where his primary interests are digital communications and DSP. John has eight patents and is currently applying for four more. □□