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,

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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

[1]Notes appear on page 34.

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

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 cur-

rently 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
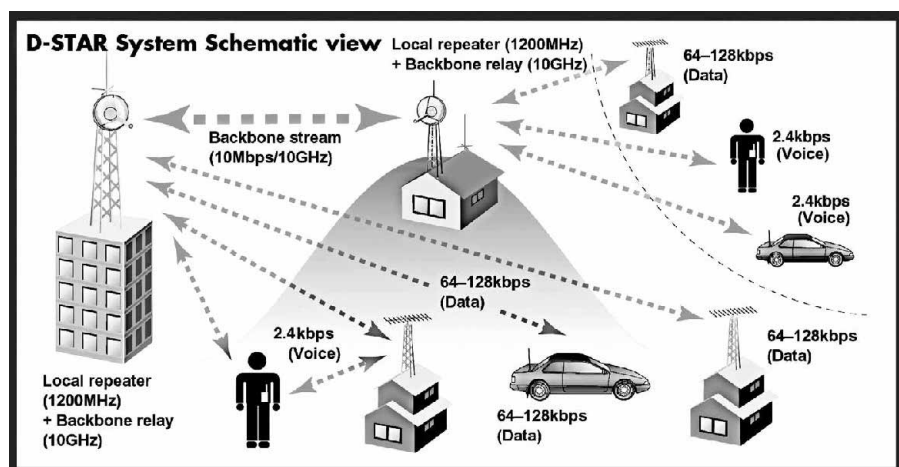

Fig 1—JARL's proposed D-STAR system offers digital voice and data communication on 1.2-GHz with repeaters linked on 10 GHz and Internet gateways.

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

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.

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D-STAR, Part 2: Design Considerations

Come learn what JARL put into their proposed new VHF communication standard.

By John Gibbs, KC7YXD

In the first segment of this series, we considered the attributes we would like to see in any new VHF/UHF Amateur Radio system. In this second segment, we discuss the technical issues involved with selecting the parameters of an Amateur Radio digital system to meet those attributes.

Perhaps the easiest way to organize the design considerations for a digital radio system is to use the OSI Model. The OSI Model is officially known as The Basic Reference Model for Open Systems Interconnection. We start the description with the bottom level of the OSI model, the physical layer. Then we will work our way up to the top levels, which are open to amateur experimentation and application development.

Physical Layer

Transceiver Frequency

We hams have a large spectrum allocation at 1.2 GHz (60 MHz wide in

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the US) that is little used today. In fact, we should use this spectrum or risk losing it to commercial interests. Also, if we want to develop a system to send high-speed data, we will need a wide-bandwidth signal and there is little available spectrum at 70 cm. If it is desired to use the D-STAR protocol at lower frequencies, the high-speed data mode could be dropped. In fact, a prototype portable 2-m HT using only the digital voice mode has been developed and was shown this spring at IWCE.

Like the previous FM system, the system design logically calls for half-duplex operation for digital voice and simplex for high-speed data.

Repeater Link Frequency

Since it is desired to have multiple contacts and high-speed data packets on the repeater link, a wide bandwidth is required. Therefore the repeater backbone must be at microwave frequencies and the amateur band at 10 GHz is a logical choice. Today's equipment generates usable 10 GHz power, is affordable and the 10 MHz of bandwidth is practical. The bi-directional, asynchronous nature of multiple contacts demands a full-duplex repeater link.

Given the high-speed data requirements of the system and the desire to use digital voice to reduce transceiver spectrum requirements, the repeater link should be digital. With the asynchronous nature of the system, packet mode is a natural choice. However, because a packet system does not guarantee real-time communication, voice should be given priority over data to minimize the possibility of voice disruptions.

Modulation

An ideal modulation system should generate a signal that has a narrow spectrum, with low side lobes so that it does not interfere with other nearby users. On our crowded ham bands, this is becoming more of an issue daily.

There are several commonly used modulations for digital data. The digital modulation scheme chosen will significantly affect the performance of a communication system. Generally we want to maximize the data rate within

the constraints of acceptable level of latency, available bandwidth, acceptable error rate, product costs and operating environment (that is mobile, portable, fixed-link). In particular, mobile and portable operation causes variable multipath fading and fast phase shifts that can wreak havoc with digital radios.

Less spectrally efficient modulations generally have better operation characteristics in poorer SNR conditions. Also, they are more forgiving of frequency-offset errors between the transmitter and receiver and frequency and phase response error on the channel—an important consideration if costs are to be kept down in a UHF system.

4 FSK—FSK, MSK and GMSK are very attractive because they are constant amplitude modulation. This means that the power amplifier can be class C, which offers low cost and excellent power efficiency.

FSK has of course been used in amateur systems for years, dating back at least to the introduction of RTTY. Newer variations on FSK use more frequencies than just mark and space. For instance, the new weak signal mode, JT44 uses very slow FSK (about 5 Hz data rate) with 44 different frequencies each corresponding to a character.[1] But at the higher data rates needed for a VHF/UHF digital voice system, four FSK frequencies offers an attractive option for improved FSK performance.

GMSK—Among FSK, MSK and GMSK, GMSK offers the best spectral efficiency with only a slight degradation in the BER compared to FSK and MSK. These advantages have made GMSK one of the most popular digital modulations worldwide. Other more complex modulations like QPSK require a more expensive linear power amplifier that also typically requires more current, which is critical in portable operation.

GMSK low-pass-filters the data stream with a filter that approximates a Gaussian time and frequency response. A Gaussian filter is used because of its desirable properties in both the time and frequency domains. This filtering reduces the high-frequency content of the modulation and therefore narrows the frequency spectrum of the modulated signal while widening the data response minimally. However, as you continue to narrow the filter, the spectrum continues to narrow and the time response of the filter lengthens. This causes the peak amplitude to decrease and the adjacent data tails of the time response to

[1]Notes appear on page 28.

interfere with the decoding of the desired symbol, a phenomenon called inter-symbol interference (ISI).

A typical compromise between ISI and bandwidth used by many systems is for the bandwidth/data rate ratio to be equal to 0.5. This yields almost no degradation due to ISI compared to MSK and yet dramatically reduces the spectral occupancy of GMSK compared to MSK.

QPSK—In theory, quadrature phase-shift modulation could have a constant amplitude format. However, the rapid switching of the input data causes a QPSK signal to have large sidebands that destroy its spectral efficiency. Therefore in practice, raised cosine filters are used on input data to reduce these sidebands. To preserve the wave shape induced by these filters requires the use of a more expensive and less power-efficient linear amplifier. If a class-C amplifier were used with QPSK, the sidebands that were removed by the cosine filter would be regenerated.

In the presence of additive white Gaussian noise (AWGN), QPSK requires about 3 dB less signal-to-noise than does FSK. However, in real channels, with multipath and poorly synchronized receivers, the 3-dB advantage quickly disappears.

Data Link Layer

Time Division Multiple Access (TDMA)

TDMA is one of the two commonly used multiplexing standards for cellular phones. The cell tower site acts as the master clock and assigns a time slot to each of several cell phones that are assigned the same frequency. For proper operation, it is critical that each phone transmit and receive exactly in its assigned time slot. This is not attractive for amateur simplex operations because operations are as two or more equals, and there is no master to determine the clock and assign time slots.

Any Amateur Radio system has to work without a centralized frequency reference and master clock. In addition, the radios must be able to acquire signals that are somewhat off frequency and acquire timing without the need for a separately transmitted clock signal. These requirements may make an amateur system less spectrally efficient than a centrally-controlled system like the cell phone, but they are more in keeping with the spirit of Amateur Radio, particularly the capability to operate when the infrastructure is destroyed.

Code Division Multiple Access (CDMA)

CDMA (also known as spread spec-

trum) is also used for multiplexing cellular phones. In CDMA, several cell phones share the same frequency and transmit simultaneously. Each phone on a frequency is modulated with a code sequence that spreads the spectrum in a unique way. If the receiver is synchronized and has the same code sequence, then the signal is restored. Otherwise, the signals from other phones become part of the background noise.

An important limitation on the system is that undesired signals are not completely rejected. Depending on the length of the codes used and the attendant difficulty in synchronizing, perhaps 20-30 dB of so-called processing gain can be attained. Therefore, a strong nearby CDMA signal can overpower a more distant signal. This classic problem with spread-spectrum communications is called "the near-far problem."

In a cell-phone system, this problem is addressed by power control. Since all the nearby phones are communicating with the same nearby cell site, the cell site remotely controls the power level of each phone to minimize the possibility of interference. However, in Amateur Radio, particularly with multiple simplex contacts, this is not a solution.

Frequency Domain Multiplexing (FDM)

TDMA, CDMA and other modern multiplexing schemes require coordination between the units that is incompatible with the basic goals of the Amateur Radio Service. One of the major justifications for our service in the US is emergency service. TDMA and CDMA require an infrastructure to provide the coordination. This infrastructure would quite possibly be destroyed in an emergency. So, the best solution for Amateur Radio is what we have traditionally used, FDM.

Network Layer

In the network layer, the binary data stream is divided into discrete packets of finite length. In addition, error checking is performed by cyclic redundancy check (CRC) at this level. If an error is detected, it is corrected by the retransmission of packets.

Transport Layer

In the transport layer, we multiplex and split all the data streams we need to send and receive. In an Amateur Radio system, we would typically need to include repeater control data; source, destination and routing information (that is, call signs of both operators and repeaters used); and what is called the payload, which is the voice or data to be sent.

Presentation Layer

Codec

As mentioned in the first segment of this series, simple PCM encoding of voice results in a 64,000 bits/s data stream. Codecs have been developed to compress voice with good quality down to 2400 bits/s and lower. These codecs develop their extreme data compression by modeling short segments of the human voice and only transmitting the reduced information needed to describe the voice model.

One of the major difficulties in designing a digital voice radio is in testing the voice quality. High-compression codecs are designed to work with a human voice; traditional tests like frequency response and harmonic distortion with sinusoidal tones do not generate meaningful results. Consequently, a subjective method of testing called *mean opinion score* (MOS) has been developed. MOS is estimated by a test with a group of normal listeners who are asked their opinion on a five-point scale (1 = bad, 5 = excellent) and the results are averaged together.[2]

A very important factor in conducting MOS tests is the acoustical environment. Since the codec is designed to highly compress the information in a human voice, it is easy to imagine that the presence of other signals and noise can severely affect the performance of the system. An excellent test for Amateur Radio is performance in an automotive environment including engine noise and wind noise from an open window.

A final issue in codec selection is the MOS performance in the presence of the channel impairments we commonly find in VHF/UHF communication paths. As Digital Voice Systems point out on their Web site, "Vocoders...designed for extremely low bit-error rates, such as those encountered in land-line communications, often experience serious degradation when applied to the much higher bit-error rates found in wireless communications. Consequently, it is important to consider robustness to channel degradations during the vocoder-algorithm design process."

Scrambling

Bit synchronization and accurate level slicing in the receiver require frequent transitions in the data (no long

Table 1—D-STAR Transmission Characteristics

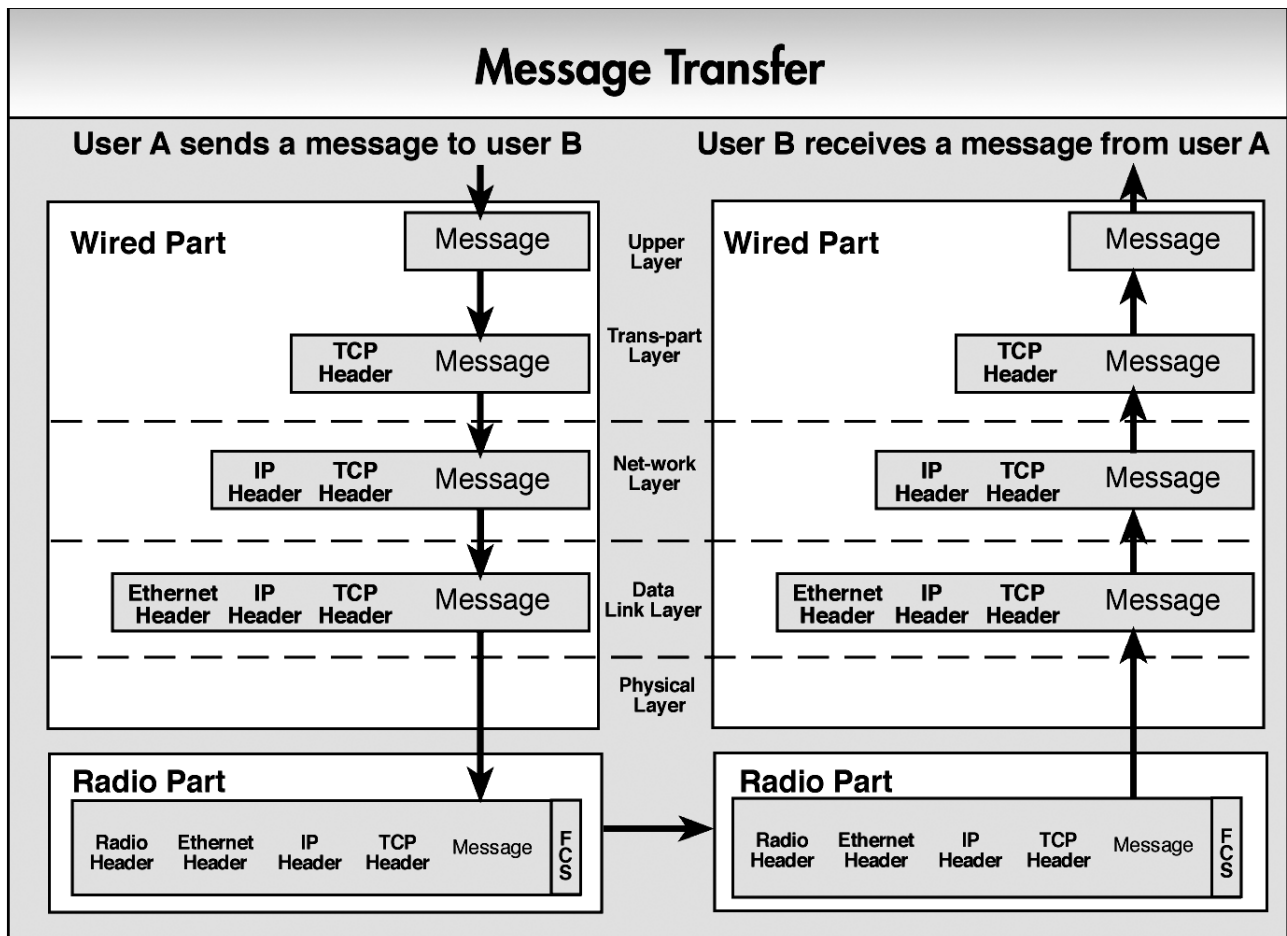| Mode	Transmission Speed	Bandwidth
Backbone	10 Mbps or less	10.5 MHz
Data	128 kbps or less	130 kHz
Digital Voice		
ITU	8 kbps	9 kHz
AMBE	2.4 kbps	5 kHz

Fig 1—Header additions with TCP/IP protocol.

strings of ones or zeros). To ensure that condition, most digital radio systems use a device called a scrambler to randomize the input data stream.

"Scrambler" is an unfortunate term for people who are familiar with analog radios; it is common to interpret this as encryption. The FCC of course forbids encryption for amateurs. Scrambling is not an attempt to hide the message content, however; it is a fixed and published method known by all potential receivers for converting the input data stream into a data stream with short strings of ones or zeros.

Scrambling is typically done with a shift register and exclusive **OR** gates. CCITT recommendation V.26 recommends this procedure.

Application Layer

This is the layer where hams can begin to customize the system and add their own applications. In addition, this is the level where the system design allows for user control entry and data entry, both data from the IEEE 10BaseT Ethernet and analog audio from the microphone.

D-STAR Proposed Standards

As stated in the first part of this article, D-STAR is not a finalized standard at the time of this writing. However, the field trials are finished and standard publication begins here. Table 1 shows the system as it stands at this writing.

To describe the proposed D-STAR standard, we will start at the input side of the transceiver and work our way out to the antenna, working our way down the OSI model. We will then see how the standard defines the repeater operation and the links between repeaters. First we will consider the high-speed data mode and then the digital voice.

High-Speed Data

The standard interface for high-speed data into and from the D-Star system is IEEE802.3 (10BaseT Ethernet.) In Fig 1 you can see how the D-STAR transmitter adds a radio header extension to the Ethernet message just as the Ethernet protocol added a header to the Internet Protocol, TCP/IP. Since this radio header is stripped off in the receiver, the radio link appears to be a "wireless Ethernet cable." Therefore, it is possible using existing software (such as browsers) to communicate the same images, text and voice as is handled by Ethernet, including links to the Internet, without modification.

Data Multiplexing

Fig 2 shows the details of a communication packet from the radio part in Fig 1. Each packet consists of a radio header and the Ethernet packet described above followed by an error-checking frame. The radio header is worthwhile to study in some depth as it shows many of the D-STAR system capabilities.

Each frame of the radio header is identical in both the high-speed data

mode and in the digital voice mode. If the standard is approved as proposed, it will contain the following information:

The first two fields are common to most digital radios, the bit sync and the frame sync. These preambles are designed to allow the receive modem to establish timing and level lock as quickly as possible.

The flag field describes the content of the data field.

Bit 7 Data or voice communication flag.
Bit 6 Repeater or simplex flag.
Bit 5 Communication-interruption flag.
Bit 4 Control signal, data or voice signal flag.
Bit 3 Emergency/normal signal flag.
Bits 2-0 Transmission-control bits (see below).

The ID field can hold four call signs:
1. The local repeater you are accessing (optional).
2. The linked distant repeater the called party is using (optional).
3. The station you are calling (can be CQ).
4. Your own call sign.

The PFCS field is a check word for the header. Some of these bits require a little more explanation if we are to understand the operation of the system. Notice that when bit 3 of the flag field is set, you are asking for an emergency break-in. (On many FM repeaters you would say "break" today.) For

Data Mode Message Transfer Details

Radio Header									Data					FCS
			ID							MAC Header			Data Frame	CRC
Bit Sync	Frame Sync	Flag	Destination Repeater Callsign	Departure Repeater Callsign	Companion Callsign	Own Callsign	PFCS	ELen		SA	DA	Type		
64bit	15bit	1byte	8byte	8byte	8byte	8byte	2byte	2byte		6byte	6byte	2byte	46-1500byte	4byte

Fig 2—Proposed bit pattern in high-speed digital mode.

Table 2—Call-Sign Combinations and the System Function

(Uses Evergreen Intertie Call sign examples[3])

Called Station	Departure Repeater	Destination Repeater	Own Station	Function
CQCQCQ	KB7WUK	K7NWS	KC7YXD	CQ Portland
N7ABC	KB7WUK	K7NWS	KC7YXD	Call N7ABC in Portland
N7ABC	K7NWS	K7NWS	KC7YXD	Call N7ABC on local repeater
N7ABC	DIRECT	DIRECT	KC7YXD	Simplex

instance if you want to report an accident, pushing the emergency key on the radio will set bit 3 and all D-STAR radios within range will open squelch and their volume to be set high.

The flag field bits 0, 1 and 2 are used for transmission control. They implement functions like ACK, ARQ and repeater control.

One of these repeater control functions is repeater lockout. Repeater lockout is used mainly to block illegal stations. A D-STAR repeater can hold a black list of call signs that have consistently violated repeater and/or FCC rules. If a blacklisted station calls the repeater, the repeater does not repeat the message but instead calls the offending station back with the lockout bit set. The offending station's radio will then display a message indicating that it is blocked from the repeater. So now, it is not necessary to shut down the repeater for everyone when one individual is misusing the repeater.

Another important field for understanding the capabilities of the system is the ID field. Understanding the ID field is important because it shows the great flexibility available in the system calling capabilities. The first thing to notice is that the D-STAR protocol automatically IDs at every transmission. This easily meets the FCC ID requirements for ID at start, end and every 10 minutes of transmission.

Next, to understand how the four ID fields work, Table 2 illustrates the contents of each field if KC7YXD were to transmit on a fictional D-STAR Evergreen Inter-tie system. It is not necessary to always fill in all the ID fields. If you respond to a CQ or a call directed at you, your D-STAR transceiver will automatically fill in the fields for you.

Digital Voice

Codec—Those of you who had a chance to see the D-STAR presentation at last year's Dayton Hamvention or at the DCC in Denver last fall may recall that the Digital Voice mode occupied 8 kHz of bandwidth using the ITU G.723.1 Codec standard. At that time,

the two codecs were undergoing field trials; today the JARL has selected AMBE as the standard. The two standards under consideration were the ITU standard G723.1 and a Digital Voice Systems proprietary codec that uses the AMBE algorithm.

ITU G.723.1 uses an ACELP (algebraic code-excited linear prediction) algorithm that generates a 5.3-kbps data stream. With an algorithm delay of 37 ms, the total wireless-communication-throughput delay is a little over 100 ms, quite reasonable for half-duplex communications.

AMBE stands for advanced multi-band excitation. AMBE can use different levels of compression to trade off voice quality and bit rate. Tests show that at the 2.4-kbps data rate, the voice quality was at least as good as the higher-data-rate ITU G.723.1 over real radio links. The algorithmic delay is only slightly longer than G723.1 (44 ms), so the factor-of-two improvement in data rate (and spectral efficiency) comes with no noticeable latency increase.

The data-rate reduction from the AMBE codec is particularly significant because of worldwide pressure from regulatory agencies to reduce the occupied bandwidth of voice communications sufficiently to allow 6.25-kHz signal spacing. When using a modulation scheme sufficiently robust to give reliable communication in mobile and portable applications, only the AMBE data rate meets this signal-spacing requirement.

The decision between codecs is complicated by the fact that G.723.1 is an

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Table 3—AMBE Vocoder-Based Systems

Inmarsat
Thuraya
Iridium
APCO Project 25 (IMBE)
G4GUO & G4JNT HF Digital Voice System

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open public standard codec whereas AMBE is the patented intellectual property of Digital Voice Systems. Unlike many companies, however, the present owner of this technology supports the Amateur Radio community and is willing to sell these parts in small quantities.

The JARL is not alone in deciding on AMBE for its high voice quality and very low bit rate. Table 3 shows several digital systems that have standardized on this codec technology. For instance, the Telecommunications Industry Association (TIA) selected DSVI's codec technology over CELP and other codecs for the APCO Project 25 North American land-mobile radio-communication system. This is particularly significant because at least two Amateur Radio groups are evaluating Project 25 radios as an alternative digital radio standard for amateur usage.

Fig 3 illustrates the bit pattern used in the digital voice mode when the AMBE codec is used. As mentioned before, the radio header is identical to the high-speed digital mode radio header and so will not be discussed here.

The most interesting part of Fig 3 is that the digital-voice data frames are interleaved with data frames. These frames are currently reserved by the D-STAR standard with no dedicated usage by the system overhead. This means that the system is capable of supporting a 2400-bits/s data stream from a user application while the user is talking on the system! Notice that the D-STAR system itself provides no error detection for this data, so it would be up to the user's application to provide error detection and error correction. This and other overhead would decrease the end-to-end data rate slightly; but if radios are built to exploit this capability, hams could potentially add many interesting features to the D-STAR system.

What is not shown in Fig 3 is that the frame and sync fields are repeated often so that the errors between the transmitter and receiver clocks can be

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Voice Mode Message Transfer Details

			Radio Header					Data						
					ID									
Bit Sync	Frame Sync	Flag	Destination Repeater Callsign	Departure Repeater Callsign	Companion Callsign	Own Callsign	PFCS	Voice Frame	Data Frame	Voice Frame	Data Frame	_ _	Voice Frame	Last Frame
64bit	15bit	1byte	8byte	8byte	8byte	8byte	2byte	48bit	48bit	48bit	48bbit		48bit	48bit

Fig 3—Bit pattern in digital-voice mode.

corrected without requiring a master clock signal. It also means that another amateur can tune into the middle of a contact and listen to the conversation without waiting for the sync frames of the radio header at the next over.

Modulation

Several modulation methods were investigated during the development of the D-STAR standard. Modulations tested included GMSK, FSK, 4-FSK, MSK and QPSK. GMSK has been selected for the backbone line between repeaters. The standard for the portable and mobile transceivers may include more than one modulation format.

Gaussian minimum-shift keying (GMSK) and quadrature phase-shift keying (QPSK) are the two finalists. A third, 4-FSK, has been recently proposed as an alternate standard and is now under investigation. The reason for the delay is that selecting the best modulation for D-STAR real world applications is not a trivial exercise. In real mobile communications systems, the link between a moving node and a base station will be subject to multipath, which results in Rayleigh fading. This will have a significant effect on the resultant BER performance, possibly increasing the required C/N for a specific BER by as much as 10 dB.

QPSK is commonly used in fixed-link communication systems. Under ideal conditions, QPSK would give better performance than GMSK or 4-FSK and its higher spectral efficiency is obviously attractive. However, QPSK's higher spectral efficiency also leads to higher susceptibility to transmission impairments such as multipath and phase hits. Yet, the biggest disadvantage of QPSK is the need for extremely linear power amplifiers to avoid spectral growth—what we Amateurs call splatter.

The front-runner at the time this article is written is GMSK. In its favor, GMSK is a well-proven technology, and probably the most commonly used digital modulation in the world for portable applications (see Table 4). GMSK has two basic advantages. First, it is more robust than QPSK to common transmission impairments. Second, GMSK, as a form of FSK, has constant amplitude and can therefore use very efficient class-C power amplifiers. Third, GMSK is not as sensitive to frequency errors between the transmitter and receiver. Because no master frequency reference is available in the D-STAR system, tuning errors on a 1.2-GHz signal can be

substantial, particularly with the extremes of temperature found in portable operation. The alternatives are to suffer the expense of a precision frequency reference in all the radios or adopt a modulation method like GMSK that is more tolerant of frequency errors.

However, GMSK is not so spectrally efficient as QPSK. For instance, at 128 kbps, GMSK with a BT product of $^1/_2$ occupies a bandwidth of 135 kHz. For the same data rate, QPSK requires only 83 kHz.

The best solution is probably to use a codec with the AMBE algorithm described earlier that reduces the data rate as far as possible and then use GMSK for more robust communications, but the tests still continue.

Fig 4 is a somewhat busy graph that dramatically shows the difference in occupied bandwidth. The existing FM system bandwidth can be determined by Carson's Rule to be about 16 kHz. While not all combinations of modulation and codec algorithms are shown, you can clearly see that you can fit many more digital voice contacts into the same spectrum.
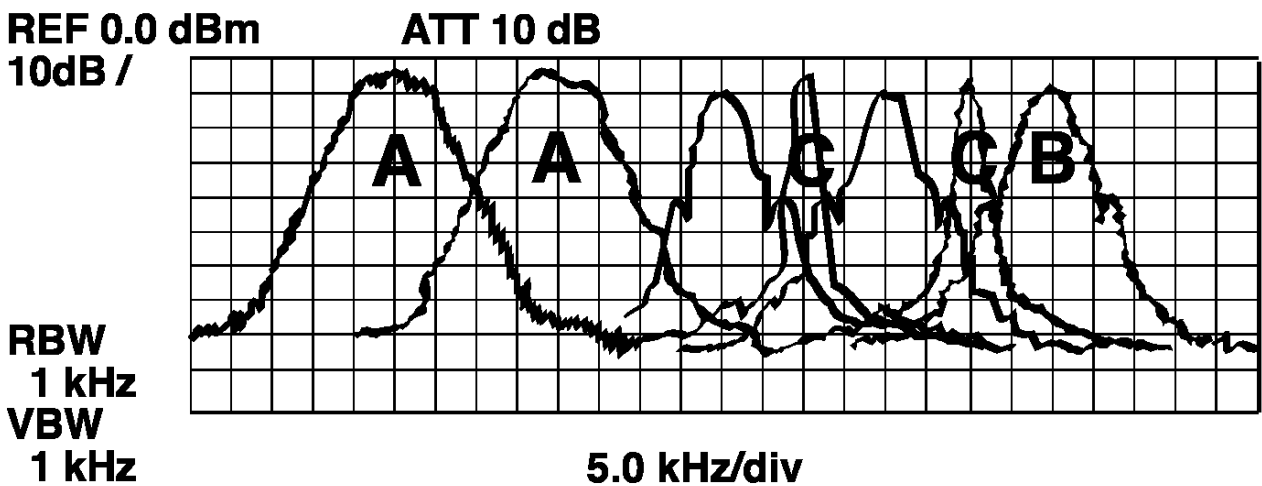
Repeater

The digital voice mode is half-duplex with a 20-MHz offset between transmit and receive frequencies. High-speed data is simplex.

As shown in Fig 5, much of the repeater site function is to provide a

Table 4—GMSK is used in Systems Worldwide

GSM cell phone
DECT
Cellular Digital Packet Data (CDPD)
Mobiltex

A:	Conventional FM
B:	GMSK and ITU G.723.1
C:	GMSK and 2.4 kpbs AMBE
Unmarked:	QPSK and ITU G.723.1

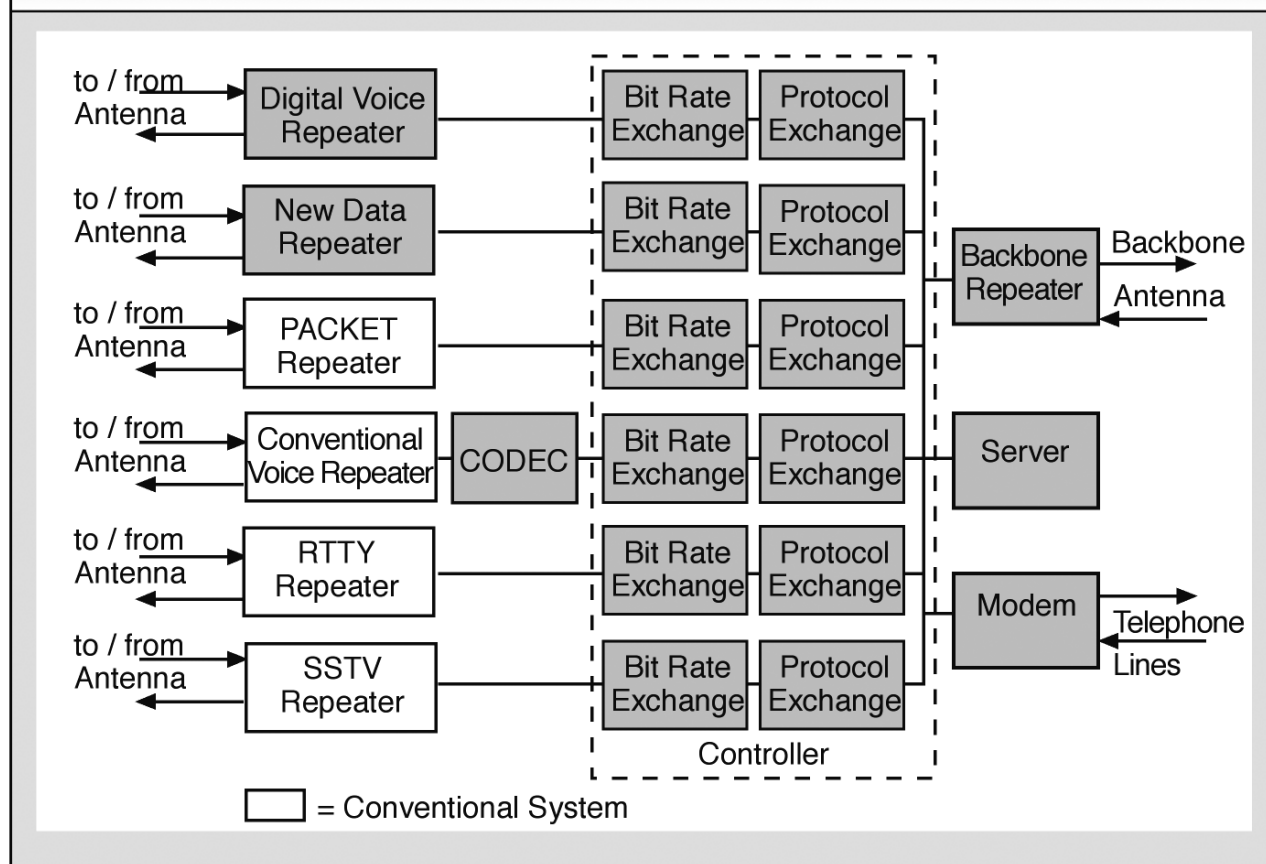Fig 4—Occupied bandwidth of digital radio.

Repeater Site Details

Fig 5—Integrated site with analog and digital radio repeaters, high-speed backbone and Internet connection.

gateway to other repeaters, both at other sites and to repeaters on different modes. The repeater also provides an interface to the repeater backbone link to the Internet if desired. The system is designed to support remote control of the repeater over radio and/or landline links.

Repeaters could be linked via the Internet instead of the backbone, but because of bandwidth limitations, much of the high-speed multiple contact capability would be lost.

Repeater Call Sign Protection

To protect repeaters from co-channel interference, CTCSS tones are used to prevent interfering signals from triggering the repeater. In the D-STAR system, the digital header contains the call sign of the repeater to be accessed. If the repeater does not see its call sign in the message, the repeater is not opened.

The Backbone Repeater Link

One of the major advantages of the D-STAR system is the full-duplex 10-MHz-bandwidth backbone link between repeaters. This wide bandwidth allows multiple voice and data contacts to occur simultaneously on the link. An analysis of the frequency of use of data and voice communications demonstrated that a 10-Mbit/s full-duplex link would support the needs of up to 12 linked repeaters.

The high-speed data and digital-voice data streams from multiple repeaters are multiplexed into a single data stream according to the asynchronous transfer mode (ATM) standard. This 10-Mbit/s data stream is GMSK modulated onto a 10-GHz carrier, resulting in an approximately 10-MHz wide signal.

The ATM cell is made up of a short 53-byte packet that consists of a 5-byte header and a 48-byte payload. The ATM cell is sent to the required destination according to the preset list that is set by the ATM switch set at each repeater site. Because the priority level can be designated in the header, voice signals arrive in real time. This avoids the delays that happen with VoIP on the existing Internet Protocol.

Backbone field tests have been carried out with a 36-dB-gain parabolic antenna and a 1-W transmitter. Heavy rains in southern Japan of more than 12 inches per hour limit the practical distance that the repeaters can be separated. It was found that taking into consideration these extreme weather conditions, the maximum range for uninterrupted communications is about 12 miles. Obviously, the fog and rainfall at the location and the acceptable probability of communication interruption dramatically affect this number.

Notes

[1]"JT44: New Digital Mode for Weak Signals," (World Above 50 MHz) *QST*, June 2002, pp 81-82.
[2]D. Smith, KF6DX, "Digital Voice: The Next New Mode?" *QST*, January 2002. For a discussion of MOS, see the sidebar, "How Do I Sound?" on pp 29.
[3]K7NWS is a Seattle, Washington, repeater and KB7WUK is a Portland, Oregon, repeater on the Evergreen Intertie. These examples assume an identical system to the Evergreen Intertie but based on D-STAR. □□

D-STAR, Part 3:•
Implementation•

We've seen the "whys" and "hows" of D-STAR. Let's look at the hardware and possible uses for the system.

By John Gibbs, KC7YXD

This article, the final part of the series, investigates the block diagram and performance of the prototype equipment to better understand the design issues of a D-STAR digital radio.

The hardware used in testing the D-STAR standard is shown in Fig 1 and the performance of the mobile unit is summarized in Table 1. Some of this hardware is available today and we expect several manufacturers will offer hardware soon.

Recall that the D-STAR standard has only recently finalized the selection of the modulation and codec. Prototype testing demonstrated that GMSK modulation and the AMBE 2020 codec gives the best combination of spectral efficiency and robust communications.

The IF and RF parts of the block diagram (see Fig 2) of the ID-1 shows a straightforward dual-conversion superheterodyne design that should look familiar to those experienced with analog rigs. However, several issues in a digital-radio IF are not clear from the block diagram.

IF Design Issues

The first issue with digital-radio IFs is that the group delay of the IF structure is critical. While analog radio designers can ignore phase linearity, group-delay variations need to be less than about 10% of the data period to avoid excessive BER due to intersymbol interference.

The second issue with digital radio IFs is that IF bandwidth must be wider than that of an equivalent analog design. It must be wider so that significant energy does not fall near the band edges of the filter because there the group delay is not constant.

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Table 1
ID-1 Specifications Summary

Operating frequency	1.2 GHz Amateur Radio Band	
Operating Modes	FM (analog voice)	
(FDMA)	0.5GMSK (digital voice / data)	
Data Rate	4.8 kbps (voice) / 128 kbps (data)	
CODEC	AMBE	
Data Interface	IEEE802.3 (10Base-T)	
RF Power	10 W/1 W	
Receive Sensitivity	FM	−16 dBu
(typical)	4.8 kbps GMSK Voice	−10 dBu
	128 kbps GMSK Data	+ 2 dBu
Switching time	10 mS (digital mode)	
GMSK Modulation	Quadrature Modulator / FPGA (baseband)	

It often rises significantly and displays what are called "ears" (from their shape). This is particularly true in the receiver IF where transmitter and receiver relative-frequency tuning errors may cause the signal to be off center in the IF. Unfortunately, this increases the noise and interfering signals that pass through to the detector.

The quality of these IFs is measured by the sensitivity numbers in the specifications and in the "eye" diagrams in Fig 3. The well-open eye means that the receiver can easily distinguish between the plus and minus signal sent and therefore decode with very little BER. Fig 4 shows how the BER improves as S/N increases in the digital voice mode.

The final issue with digital radio IFs is the quality of the local oscillators. First, as implied above, the frequency reference must be accurate and temperature-stable if communication is to be established at UHF with a reasonably wide receiver IF. Second, the close-in phase noise of the local oscillators must be kept low, particularly if QPSK and other high-data-rate modulations are used. Excess oscillator noise can increase the BER just as effectively as actual channel impairments. One of the advantages of using GMSK is its relatively low sensitivity to these receiver problems, as shown in Fig 5.

Baseband Design Issues

The baseband hardware and modulators have far more obvious differences in this digital radio block diagram in Fig 2. For instance, on the transmitter side, the audio input is immediately converted to digital form, even if the radio is in the analog FM mode. This digital information is then signal-processed digitally and modulated onto the first IF. The modulation is accomplished by an I/Q modulator made with an FPGA. When teamed with DSP, an I/Q modulator is a very versatile component that can handle any form of modulation needed in the ID-1. It is even possible to produce narrowband-FM with the digitized voice. (The analog FM feature is desired for compatibility with existing analog radios.)

D-STAR Applications

D-STAR is very much a "blank slate," waiting for amateurs to write upon it. We can exploit its capabilities for a variety of old and new uses. Here are a few of the many suggestions we have heard from the Amateur Radio community as possible applications of D-STAR.

Mobile and Portable Internet Access

The application that springs almost instantly to everyone's mind is high-speed wireless Internet access. Part of the reason is that the Internet has become such an important communication and information tool in hams' lives today. Another reason is all the hype built up around third-generation (3G) cell phones and the DOCOMO system in Japan. Yet, with today's meltdown in telecommunication commerce, it could be years before a 3G phone system is deployed in the US. So, with the deployment of D-STAR, hams could once again have a leading technology that the rest of the population would envy and that might encourage more people to get their tickets.

In support of this vision of D-STAR as an Amateur Radio community growth agent, it is interesting to watch the reaction of inactive no-code hams. For a variety of reasons, they got their tickets, but never really got interested in the hobby. Often when they see a D-STAR demonstration, you can see their eyes light up and almost hear the gears turning in their head! Several

have said that a system like D-STAR would get them active again.

Because this is Amateur Radio, there will be some restrictions on this vision of high-speed wireless Internet. The FCC does not allow encryption, so there is no guarantee of privacy. Anyone can look over your shoulder and read your e-mail.

Some hams bring up the issue of advertising and pornography. Control operators will be responsible for the content passing through their repeaters exactly as they are today. However, this does not seem to be a very difficult issue. Inexpensive software exists today that can filter out this offending material. Control operators can easily incorporate so-called "kiddy filter" software into the repeater's Internet interface. If the existing software does not quite fit our application, then resourceful hams will develop better software!

Then there is the issue of third-party traffic. Again, the control operator is responsible for ensuring that no illegal third-party traffic passes through his or her station.

Fig 1—Currently available hardware (counterclockwise, from upper right): RC-24 Control Head, ID-1 1.2 GHz transceiver, ID-RP1D 1.2 GHz data repeater, ID-RP1VS 1.2 GHz voice repeater, ID-RP1L 10 GHz backbone repeater and AH-1045/1080 parabolic antenna.
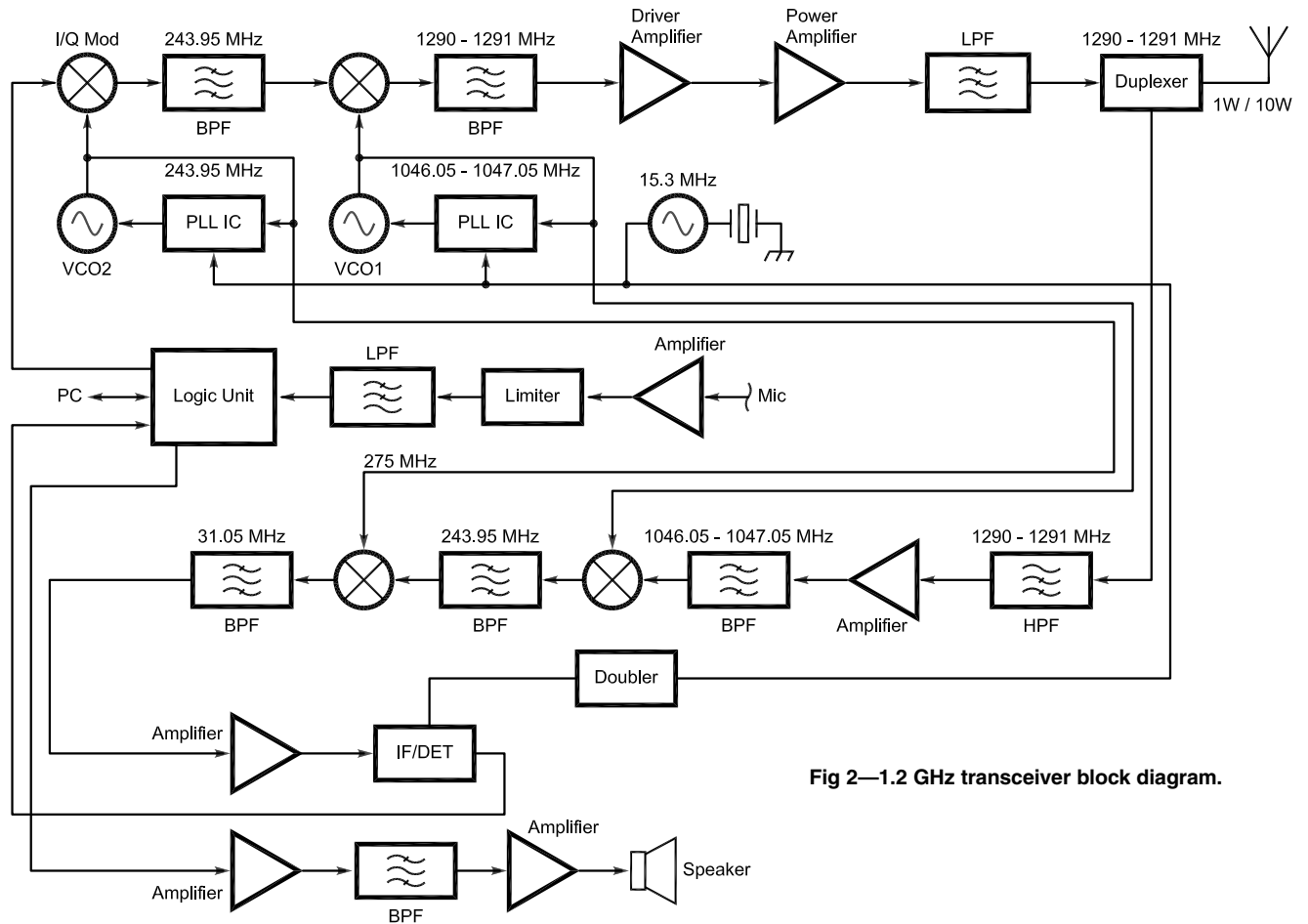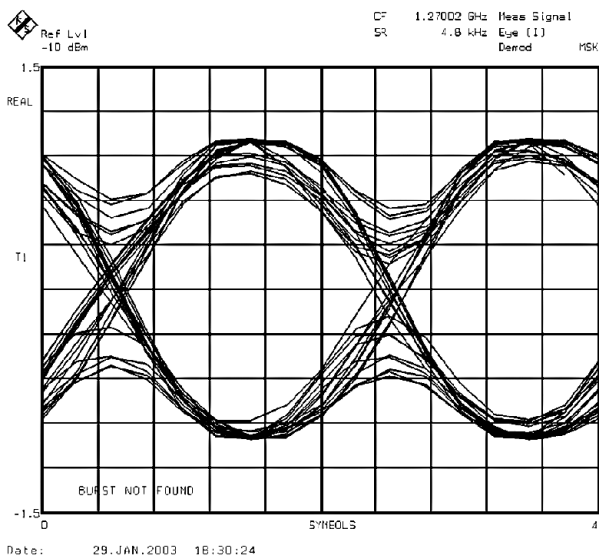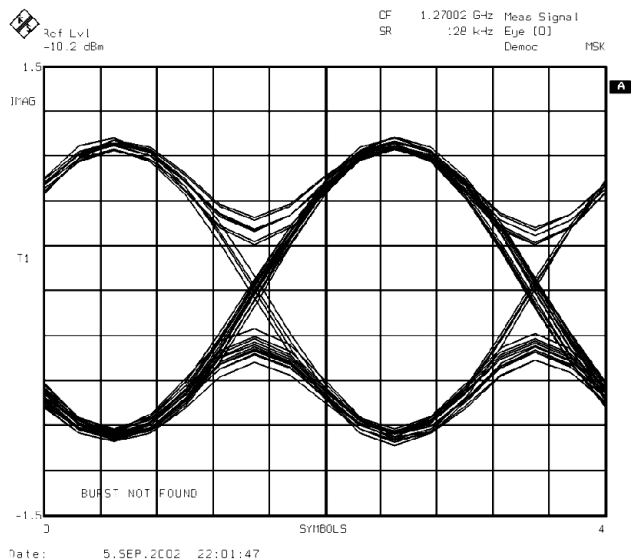
Fig 2—1.2 GHz transceiver block diagram.

Fig 3—"Eye" patterns for digital voice (A) and high-speed data (B).

Combination of 802.11 and D-STAR

It would be surprising if manufacturers did not quickly develop a handheld D-STAR-compatible radio, but the high-speed data mode will necessarily have reduced range compared to a mobile rig with a good antenna and more power. What could you do if you wanted to connect a notebook computer to the Internet, but you are beyond the limited range of a handheld?

When hams have a range problem with handhelds on today's analog FM system, they sometimes cross-band repeat using their car's mobile radio. A similar solution could be implemented for high-speed data using D-STAR and a wireless LAN access point. A D-STAR mobile in your car could be cross-band (and cross-mode) connected to an access point installed in your car. Only an Ethernet cable is needed for this connection (no PC). If you already had a wireless LAN card in your notebook computer, you would be ready to go. Your notebook computer now has high-speed Internet access with the range of the high-power mobile.

Other High-Speed Data Applications

The Internet is so pervasive today that we sometimes forget that there are many other uses for high-speed data transmission. Here are two high-speed data applications that have arisen in D-STAR discussions.

Local Amateur Intranet: Rather than connecting to the Internet, a club-sponsored repeater could offer a wireless, wide-area Intranet. What might they put on the site? It certainly is a good place to make available the repeater system's operation guide and rules. To encourage D-STAR experimentation, it would be useful to have posting of hams' experiences with the system as well as freeware and shareware that they have found useful in D-STAR operation.

Visitors to the area could download information they need, even at 3 AM. Are you looking for a good Mexican restaurant, or do you need a quiet motel away from the highway? The Intranet could have suggestions from other hams on file, and you could download maps, driving directions and even pictures.

The possibilities multiply enormously if your notebook computer has GPS. Now D-STAR can guide you exactly to your destination with accurate maps and directions that better reflect the local driving conditions than those provided by major services on the Internet. Local hams could help you avoid traffic problems caused by temporary road closures and accidents.

Emergency Communications: Another D-STAR Intranet application is emergency communications. Even if the local D-STAR repeater were knocked out, temporary repeaters could quickly be assembled using two transceivers back-to-back. Training needs are minimized by using standard Internet browsers. When an operator comes onto the system, he can easily access stored files and bring himself up-to-date on the situation without distracting others.

Possible Add-Ons and Enhancements

We wrap up this discussion of the new D-STAR system with a treatment of the possible directions in which applications might evolve. D-STAR is not meant to be a turnkey communication system like the cell-phone system. Instead, it is an infrastructure that hams can use to meet current and future communication needs. Most importantly, it is a flexible, highly capable system that allows amateurs, them-
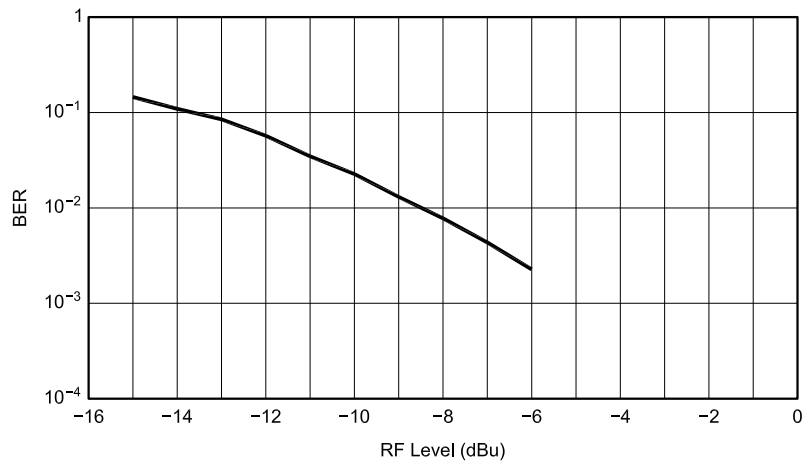

Fig 4—Bit-error rate versus RF level.

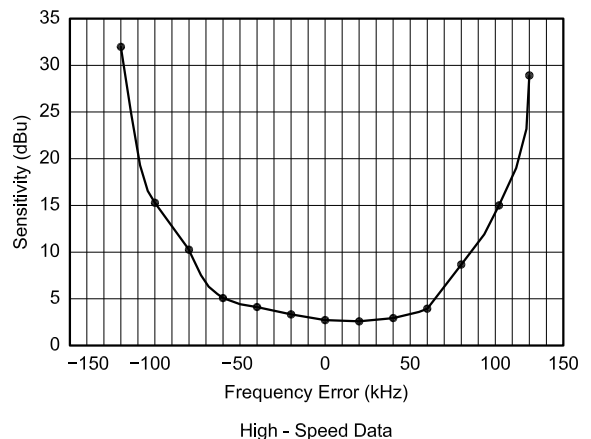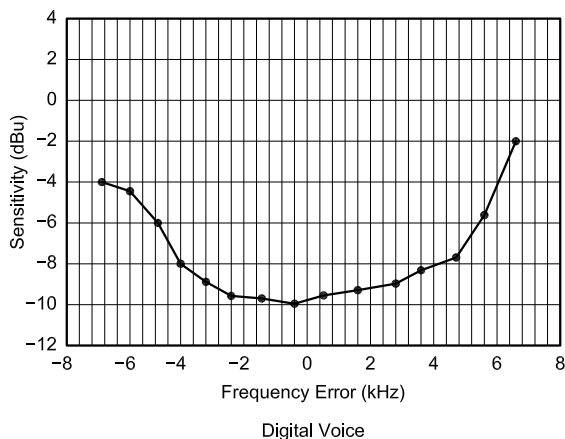Digital Voice

High - Speed Data

Fig 5—Frequency error versus sensitivity.

selves, to expand their service. Rather than depending on manufacturers to provide new features and applications, we expect the amateur community will develop add-ons to the system that will address the major goals of Amateur Radio including emergency communications, experimentation and just plain fun! Hams who have seen early demonstrations of the D-STAR system have generated the following ideas.

Power to the People!

We hams have our own opinions of how products should be designed and which features should be added. One of the great things about the D-STAR system is that for a large part, it is possible for us to try out our ideas and further the state of the art. Error correction is one area that is ripe for contribution by hams.

As data rates increase or as we push the range, decoding errors begin to be significant in any digital radio system. This is less of a problem for a properly designed digital voice system, because it is not significantly disturbed by BER levels that would render digital file transfers impossible. Yet any high-speed digital mode can use any help it can get.

Because of the importance of transferring data quickly and accurately, there has been a great deal of theoretical work done on coding and error correction. Tom McDermott, N5EG, gives a good introduction to the many coding techniques used in digital radio including Reed-Solomon, Golay and convolutional codes.[1] Newer codes called "turbo" codes have been developed that approach the theoretical limit on how fast information can be transmitted over a noisy band-limited channel.

However, these codes are only optimal if the interference is what we call AWGN (additive white Gaussian noise). This is true because the mathematics of AWGN is well understood. The bad news is that most of the impairments we find in real radio communications do not match this nice mathematical model. The good news is this is an opportunity for Amateur Radio to again advance the state of the art.

An interesting example of the possibilities of error correction is the ubiquitous CD player. A few years ago, I saw a demonstration of the power of the error correction used in CDs. The professor had drilled large holes in a CD and despite these obvious faults in the data stream, the music played perfectly without a click, pop or drop out! Perhaps some enterprising ham can discover the way to make just as

[1]Notes appear on page 47.

dramatic improvement in radio.

Interleaving Spreads Bursts of Errors

Wireless communication channels with fades of the signal power are prone to errors occurring in bursts. Burst errors can cause problems by breaking error-control codes when the number of errors exceeds the maximum number of correctable errors for the specific code used. For short bursts, intraframe interleaving improves performance by spreading the burst of errors over several different code words. For example, if four code words, each containing 23 bits that can correct up to 3-bit errors, are used in a frame consecutively, then a burst error 4 bits long will break a single code. However, if the four code words were interleaved (that is, bit 1 codeword 1, bit 1 codeword 2, bit 1 codeword 3, bit 1 codeword 4, bit 2 codeword 1, and so forth), each code word would contain only one error, which could easily be corrected. Since intraframe interleaving only modifies the bit ordering within the current frame, no additional delay is generally needed for implementation. If additional delay can be tolerated, interframe (more than just the current frame) interleaving can be used to further increase the performance with longer burst errors.

Mixed Voice and Data

As we saw in the section on the D-STAR standard, the proposed digital voice protocol has the ability to transmit low-speed user data simultaneously with voice. The first-generation D-STAR transceivers minimally support this feature. However, as new radios are introduced, it is expected that hams will develop applications that exploit this capability. Notice that in the D-STAR system, this is referred to as low-speed data. Yet the data rate is actually about 2400 baud, faster than the old 1200 baud of amateur systems (and yes, slower than the 9600 baud used in higher-speed systems).

What could we do with this feature? How about the equivalent of the Internet's "instant messaging"? With instant messaging, messages could be added by the sender or even from a third party (where legal) and added by the repeater. Imagine that you are in the middle of a contact when

• A DX alert displays on your mobile for a country you need, or
• A printer attached to your transceiver prints out route instructions to your club's Field Day site, or
• Your spouse sends you the grocery list and reminds you that the lawn needs mowing—well, maybe that

isn't such a good feature!

How about doing instant messaging one better and send instant pictures. The miniature cameras used recently in cellular phones are about 96×96 pixels; that is less than 10 kbits. So, a picture could be sent in less than 30 seconds simultaneously with a voice contact.

In a sense, this voice and data capability is like DSL: you can talk over the same channel while data are transmitted—although not at DSL speeds in this mode. The data you can send through this channel are limited only by your imagination. For instance, what do you think about mixing voice and next-generation APRS?

VoIP and D-STAR

VoIP voice communication is of course possible in the digital data mode because it does not matter what information is carried in the data. However, VoIP is not a very attractive method of communication via Amateur Radio today. It often suffers from poor voice quality scores due to the very long latency from the intensive signal processing and because the Internet does not give priority to voice packets.[2] These voice quality problems would certainly not be helped by the 128 kbps data rate of D-STAR.

Finally, VoIP on D-STAR is spectrally inefficient, requiring 130 kHz of bandwidth compared to less than 6 kHz for the highly compressed D-STAR digital voice mode. Still, for applications that require higher-speed data simultaneous with voice, inventive amateurs may find solutions to these problems.

Registration

The D-STAR proposal currently keeps a list of amateurs (call signs) who have accessed the system. So, if you want to call me, KC7YXD, you don't need to know the linking repeater. The system simply finds the repeater I last accessed and automatically routes your call to me. A logical extension of this capability is that if my radio is on the repeater frequency, the system can poll it and automatically register me onto that repeater.

This feature could be extended to keep a database at each repeater of each registered amateur's interests. How would our hobby change if you could call "CQ Collins radio collector" and automatically link to someone on the other side of the country or perhaps the other side of the world?

Roaming

Another feature that hams could add to the system is roaming. What if,

when driving through an area, the repeater could download into the radio memory the frequencies and call signs of nearby D-STAR repeaters? Then as I drive away from the repeater, the radio is all set to access the next repeater. Never again sit down with a repeater book and program the radio before the next trip!

Of course, if we were to add GPS capability and the D-STAR repeater database held the footprints, calls and frequencies of adjacent repeaters, the radio could *automatically* switch repeater sites as you drive through an area!

Trunking

"Trunking" is a land-mobile-radio term for a system that uses multiple repeaters to support many contacts at once. Most trunking systems use a "home channel" for calling, then the system assigns a clear repeater frequency to complete the contact. The radios then automatically go to the assigned frequency. The basic advantage of trunking is that the system can support many more users simultaneously than with individual systems. Effectively, it lets one listen to all repeaters in an area by only monitoring

the home channel for a call. Since the D-STAR system sends call signs digitally, it is easy to envision a simple computer program that would monitor the home channel and alert me when I am being called.

Conclusion

Clearly, Amateur Radio is at a crossroads today. Technical and regulatory forces are pushing us out of our well-proven but inefficient ways. The possibilities that digital radio brings to our hobby are truly limited only by our imagination.

I hope this article has stirred your imagination and stimulated your interest in the possibilities of digital voice and high-speed data in Amateur Radio today. Perhaps you will be inspired to try the D-STAR system and maybe even develop applications or variations of the D-STAR system.

Recommended Reading
Visit **www.dvsinc.com** to read more about AMBE and to hear voice samples at various coding rates.
D.W. Griffin and J.S. Lim, "Multiband Excitation Vocoder," *IEEE Transactions on Acoustics, Speech and Signal Processing*, Vol 36, No 8, August 1988, pp 1223-1235.
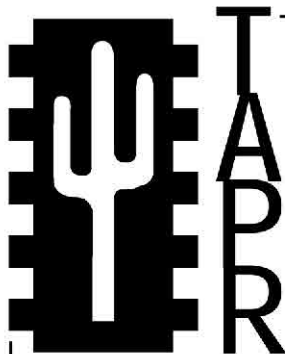
Notes
[1]*Wireless Digital Communications: Design and Theory,* Tom McCermott, N5EG, Tucson Amateur Packet Radio Corporation, 1996.
[2]The D-STAR digital voice mode addresses this problem by giving real-time data, such as voice, priority over repeater links.
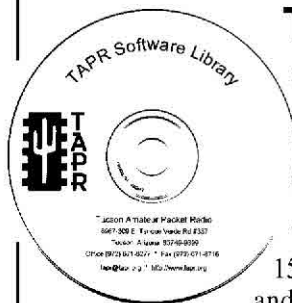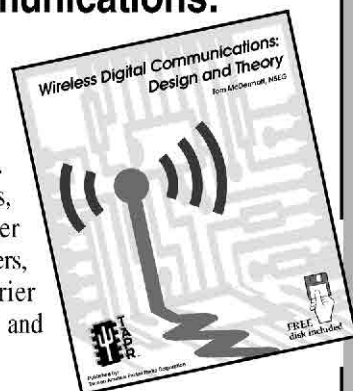
At age 3, John exhibited early talents in electronics by "helping" his dad fix a TV. He plugged the speaker into a wall socket! Despite this traumatic start, he spent his youth building Heathkit and EICO equipment, repairing vacuum-tube radios and TVs and designing and building numerous homebrew projects 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.

An Extra class license holder, John usually is found on the HF bands, primarily operating PSK31. □□