D-STAR® Uncovered

Peter Loveall AE5PL

Abstract

D-STAR®i is a digital streaming over-the-air protocol developed by the Japan Amateur Radio League, Inc. (JARL) which supports Ethernet at 128 kbps (DD) and digital voice at 4800 bps (DV). DV uses 3600 bps for voice (2400 AMBE encoding, 1200 bps FEC) and 1200 bps for synchronization and multiuse (approximately 900 bps is available for general use). DD provides an encapsulated Ethernet bridge for connecting two or more Ethernet clients over RF. We will explore this bit streaming protocol, its primary components, and current implementations. This paper explores the protocol from a technical, not subjective, viewpoint.

Keywords

D-STAR, D-PRS, Icom

Introduction

Icom Incorporated Corporation has introduced a number of radios with D-STAR® capability. D-STAR is comprised of the digital voice (DV) protocol (4800 bps) and the digital data (DD) protocol (128 kbps). D-STAR® was developed by the Japan Amateur Radio League, Inc. to support digital bit streaming modes of communication in the VHF, UHF, and higher Amateur bands. D-STAR® is an open protocol. The voice codec (vocoder) used for digital voice (DV) is the proprietary AMBE algorithm developed by the same company that owns the P25 voice algorithm. (Japan Amateur Radio League, Inc., 2005)

The DV and DD protocols are highly misunderstood primarily due to our preconceptions of a digital protocol and the lack of well translated documents. Also misunderstood is the RF framing information carried in both protocols. We will try to push through these misconceptions to expose a very powerful and forward-thinking protocol specification. We will also delineate the differences between the basic D-STAR specification and the Icom enhancements.

D-STAR uses the GMSK transmission medium and has no compatibility with existing amateur radio digital transmissions. For instance, D-STAR (bit streaming) is not directly compatible with AX.25 (packet) networks. As with any digital protocols, networks designed around one protocol are not directly compatible with another independently developed protocol.

This paper will first address the content portion of each protocol so the characteristics of the "data" is well understood before we address the D-STAR wrapper which is used for routing, identification, and other protocol-specific information. Finally, this paper addresses enhancements that Icom has built into their radios so it is understood what is part of the D-STAR specification and what are Icom enhancements.

Digital Voice (DV)

The Digital Voice (DV) specification is well-defined in the translated D-STAR specification. The content bit stream is defined as 72 bits of voice information followed by 24 bits of loosely defined "data". This pattern of 96 bits is repeated for the entirety of the transmission.
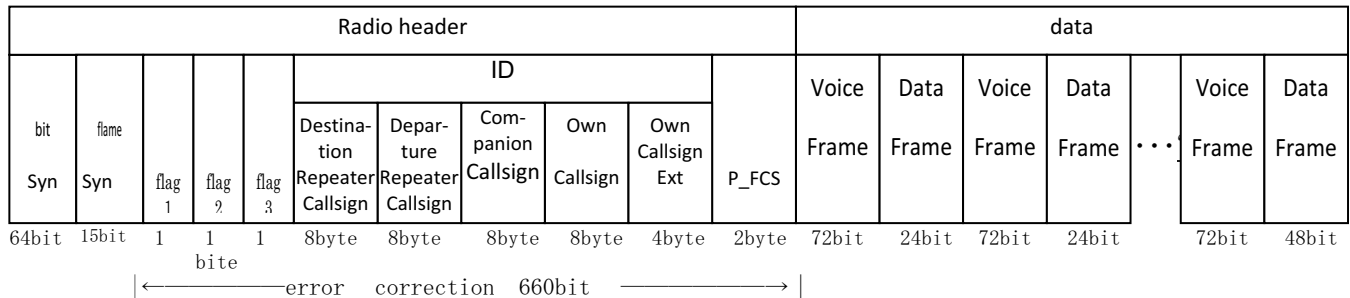
					Radio header							data						
						ID						Voice	Data	Voice	Data		Voice	Data
bit	flame	flag 1	flag 2	flag 3	Destina-tion Repeater Callsign	Depar-ture Repeater Callsign	Com-panion Callsign	Own Callsign	Own Callsign Ext	P_FCS		Frame	Frame	Frame	Frame	•••	Frame	Frame
Syn	Syn																	
64bit	15bit	1	1 bite	1	8byte	8byte	8byte	8byte	4byte	2byte		72bit	24bit	72bit	24bit		72bit	48bit

|←————————error correction 660bit ————————→|

Figure 1: Digital Voice Components

The RF header will be addressed later in this paper. The "voice frame" consists of encoded voice and forward error correction (FEC) defined as part of the AMBE algorithm. The AMBE encoding is defined as being the only content in the voice frames ensuring compatibility with all radios that use the D-STAR protocol.

The "data frame" is defined as (edited from shogen.pdf):

 (3) The first data frame and then every 21st data frame in a repeating cycle, are used only for synchronizing data for each modulation type. Synchronization corrects for the lag between transmission and reception, including the transit time of communications.

(4) The data in a data frame is transmitted without modification from the input data. If the data is required as error correction or synchronization, these frames are processed before processing the data input.

(5) If the data signal length is greater than the length of the voice communication the transmitting switch is turned on until the completion of the data signal manually. The processing can be allowed automatically.

(6) The last data frame, which requires a means of terminating the transmition, is a unique synchronizing signal (32 bit + 15bit "0001001101011111" + "0", making 48 bits) as defined by the modulation type.

Note that the "data frame" is not a data protocol as we normally think of one. There is no specification of data information separate from the total transmission. There is no error detection or correction. The first frame and every 21st frame thereafter is reserved for synchronization. The last frame is reserved as a terminator indicator. The voice frame is always present and may not be used for anything other than the AMBE encoding.

Also note that these "frames" are not separated by anything. They are not packets. They are definitions of bit positions in the continuous DV bit stream. This precludes interleaving of transmissions by different stations. Any interleaving of bits by a repeater would be modifying the data from one station without any ability to properly identify the data as being from a different source. Any attempt to imbed the "change of source" information in the data stream defeats the D-STAR routing information.

The JARL intentionally did not define the inter-sync data frame format. This leaves it open to manufacturers and radio designers to manipulate as they see fit. These bits make up 1/4th of the total 4800 bps data stream which gives a maximum transport rate of 1142 bps (1200 * 20/21).

Icom has made use of these data frames to repeat the RF header, repeatedly send a radio-to-radio 20 character message, and for carrying rudimentary data supplied by the user. These applications are described further in the "Icom Enhancements" section of this paper. It is mentioned here so designers are aware that there is a de facto standard use of these data frames already in place as implemented by Icom which must be taken into account with any new radio design for compatibility reasons. It is also important to note that the serial port on the Icom radios does not give full access to the bits in the data frame. This last point brings the maximum transport rate of serial data presented to the serial port of an Icom radio down to about 761 bps (1142 * 2/3). If the radios have a "message" programmed in, this number is even lower.

These are primary factors for anyone designing software or hardware for D-STAR DV:

1. Voice information is always ¾ of the transmission bandwidth.
2. Even "silent" voice information can be heard due to bit errors and other control issues.
3. DV transmissions are bit streams, not packets.
    a. DV transmissions are not AX.25 compatible.
    b. DV transmissions are not interleaved.
    c. Only the bit stream is identified, not individual frames.
4. Data frames contain no forward error correction or error detection information.
5. Voice information can be accurately reconstructed because of FEC when the data frames are rendered virtually useless due to bit errors.
6. Efficiency dictates short, repetitive data containing error detection information (FCS, CRC, etc.) for accurate and reliable data reception.

Digital Data (DD)

The Digital Data (DD) specification is well-defined in the translated D-STAR specification. The content portion of the bit stream is defined as a complete Ethernet packet, including FCS up to 1500 bytes long (MTU=1500). It is important to note that the content must be an Ethernet packet (not random data). The MTU of 1500 is industry standard. However, transport over the D-STAR IP network (discussed later in this paper) may cause multiple tunnel packets to be created for one MTU-size Ethernet packet.
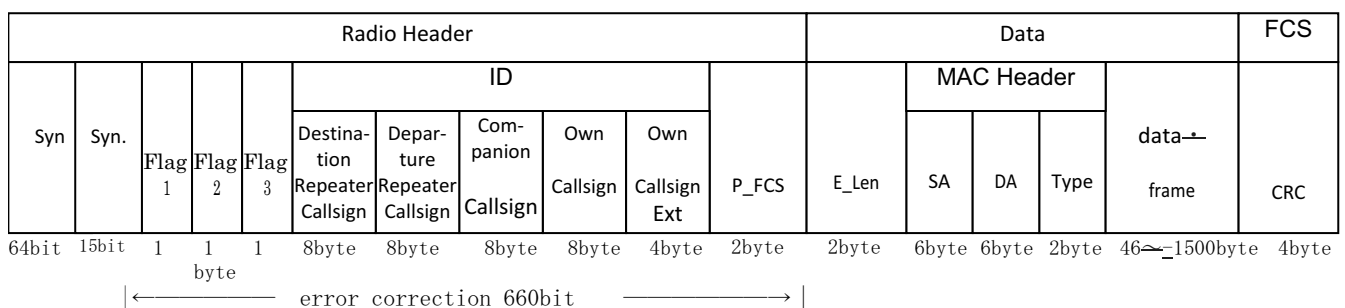
Radio Header											Data					FCS
					ID							MAC Header				
Syn	Syn.	Flag 1	Flag 2	Flag 3	Destina-tion Repeater Callsign	Depar-ture Repeater Callsign	Com-panion Callsign	Own Callsign	Own Callsign Ext	P_FCS	E_Len	SA	DA	Type	data frame	CRC
64bit	15bit	1 byte	1	1	8byte	8byte	8byte	8byte	4byte	2byte	2byte	6byte	6byte	2byte	46~1500byte	4byte

|←——— error correction 660bit ———→|

Figure 2: Digital Data Components

DD transmissions are essentially Ethernet bridge transmissions. There are no predefined restrictions on the Ethernet packet content in the D-STAR specification. While IP packets have some support in current hardware and software implementations (see "Icom Enhancement" section), any valid Ethernet packets may be exchanged between stations and still be compliant with the D-STAR specification.

Each DD transmission encompasses one and only one Ethernet packet. Any error detection and retransmission is done by the Ethernet clients. The D-STAR DD protocol provides no forward error correction safety for the Ethernet packets.

The DD protocol provides a simple Ethernet bridge over amateur radio. Because of this flexibility, it is important operationally to limit as much as possible the over-the-air communications. Broadcast protocols such as NETBIOS must be disabled if successful communications are to occur.

D-STAR Control

Every D-STAR transmission starts with synchronization bits followed by an RF header. The RF header is critical to proper interpretation of the bit stream. To ensure reliable reception of the RF header, the D-STAR specification interleaves forward error correction information and includes a 16 bit CRC for just the header information (Figure 1 & Figure 2). The full text description of the flag bytes can be found in the D-STAR specification (Japan Amateur Radio League, Inc., 2005). The only portion of the flag bytes of interest here is the bit in Flag 1 that the content is either voice or data. The rest of the flag information is used to determine repeatability, urgent status, special use, etc. that are not significant to the user but are significant to the radio designer and the designer of gateway and repeater software. Designers are encouraged to closely review these flag bytes in actual use.

The rest of the header is dedicated to "ID". This is the heart of the D-STAR protocol. The D-STAR specification defines a callsign as a 7 character sequence of upper-case ASCII characters, numbers, or spaces. All callsigns are padded with spaces to fill the 7 characters. Repeater callsigns are restricted to 6 characters or numbers with a trailing space to accommodate zone communications described later in this section. The callsign fields are always 8 bytes long (not variable). The eighth byte is the ID character. This character can be an upper-case ASCII character, a number, or a space.

"Own Callsign" is the originating station's callsign and ID. This must never be modified at any point during the repeating of the signal. "Own Callsign Ext" (Extension, 2) is a 4 character extension that facilitates reciprocal licensing prefix identification requirements or can be used by the originating station for any other purpose. It is not used by the D-STAR protocol but must not be altered as it is defined as part of the originating station identification. "Own Callsign" corresponds to "MY" in the Icom radios.

"Companion Callsign" is the callsign and ID of the station being called. D-STAR defines "CQCQCQ " as the generic "broadcast" callsign and ID. This may be a specific station callsign and ID. This may be a "zone" or "area" callsign and ID. "Zone" and "area" callsigns and IDs are repeater callsigns and IDs prefixed with a forward slash '/'. For instance, to make a call to anyone listening to the K5TIT 440 MHz DV repeater (K5TIT B), an operator would program "UR" to "/K5TIT B" on an Icom radio. Note that the repeater callsign has two trailing spaces before the ID but only one trailing space when used as a "zone" callsign. This is why a repeater callsign may only be a maximum of 6 characters while a user's callsign may be up to 7 characters.

"Departure Repeater Callsign" is the repeater callsign local to the originating station "Own Callsign". This corresponds to "RPT1" in the Icom radios. This will be spaces if simplex operation is desired.

"Destination Repeater Callsign" is the target repeater callsign LOCAL to the originating station. This corresponds to "RPT2" in the Icom radios. This will be spaces for simplex or local repeater operation. This can be set to a local repeater callsign and ID for cross-band operation (MY="AE5PL I", UR="CQCQCQ ", RPT1="K5TIT A", RPT2="K5TIT B"). This will be set to the local gateway callsign and ID (always 'G') to communicate throughout the D-STAR network (even locally) (MY="AE5PL I", UR="/K5TIT B", RPT1="K5TIT A", RPT2="K5TIT G").

The callsigns are used for all routing determination by D-STAR repeaters and gateways. D-STAR routing is designed on the premise that the operator knows who or where they want to talk to but have no need to know how their voice (or data) gets there (network-defined routing). It is also important to note that the routing is of the origin station's transmissions and does not affect the "companion" station's routing. For the "companion" to properly respond via D-STAR routing (non-local) so the origin station hears them, the "companion" station must either program UR with the origin station's callsign and ID or the zone callsign of the repeater that the origin station is using. As you will see, the preferred method is using the origin station's callsign and ID because that is all that is seen at the remote end of the transmission.

This methodology sets up the amateur radio equivalent of "Follow Me Roaming"® in the early days of cellular telephone networks. Every time a station transmits via a D-STAR repeater, that station's information is made available to the D-STAR network. This makes it possible for me to program my radio's UR with my wife's callsign and have my station callsign and ID programmed in her radio's UR, and we can communicate with each other anywhere in the world.

Key factors regarding the RF header information:

1. Flags indicate type of D-STAR transmission and miscellaneous control information.
2. "Own Callsign" 1 & 2 (extension) must never be modified
3. "Companion Callsign" is the station intended to hear the transmission.
   a. Per the precepts of amateur radio, there are no private communications (everyone with a D-STAR radio in range of the transmitting station(s) can hear the conversation).
   b. "Companion Callsign" is used by D-STAR gateways (routers) to determine the repeater to transmit on.
   c. "Companion Callsign" is used solely for D-STAR routing. Other uses such as listening only for a specific station are possible but not covered in the D-STAR specification.
4. "Departure Repeater Callsign" is the repeater local to the transmitting station. This can be modified by D-STAR gateways at the "Companion" end to be the repeater local to the "Companion".
5. "Destination Repeater Callsign" is the "second" "repeater" the transmission is to pass to/through. This will normally be the local gateway or another local repeater module. This can be modified by D-STAR gateways at the "Companion" end to be the gateway local to the "Companion".
6. No other routing information is contained in the D-STAR protocol. None may be added as any additions would break the existing networks.
7. No modification of the RF header is allowed on RF (repeaters, etc. must leave the header intact).

D-STAR Network

The D-STAR specification defines the repeater controller/gateway communications and defines the general D-STAR network architecture. The following diagram is taken from the English translation of the D-STAR specification:

Figure of System constitution
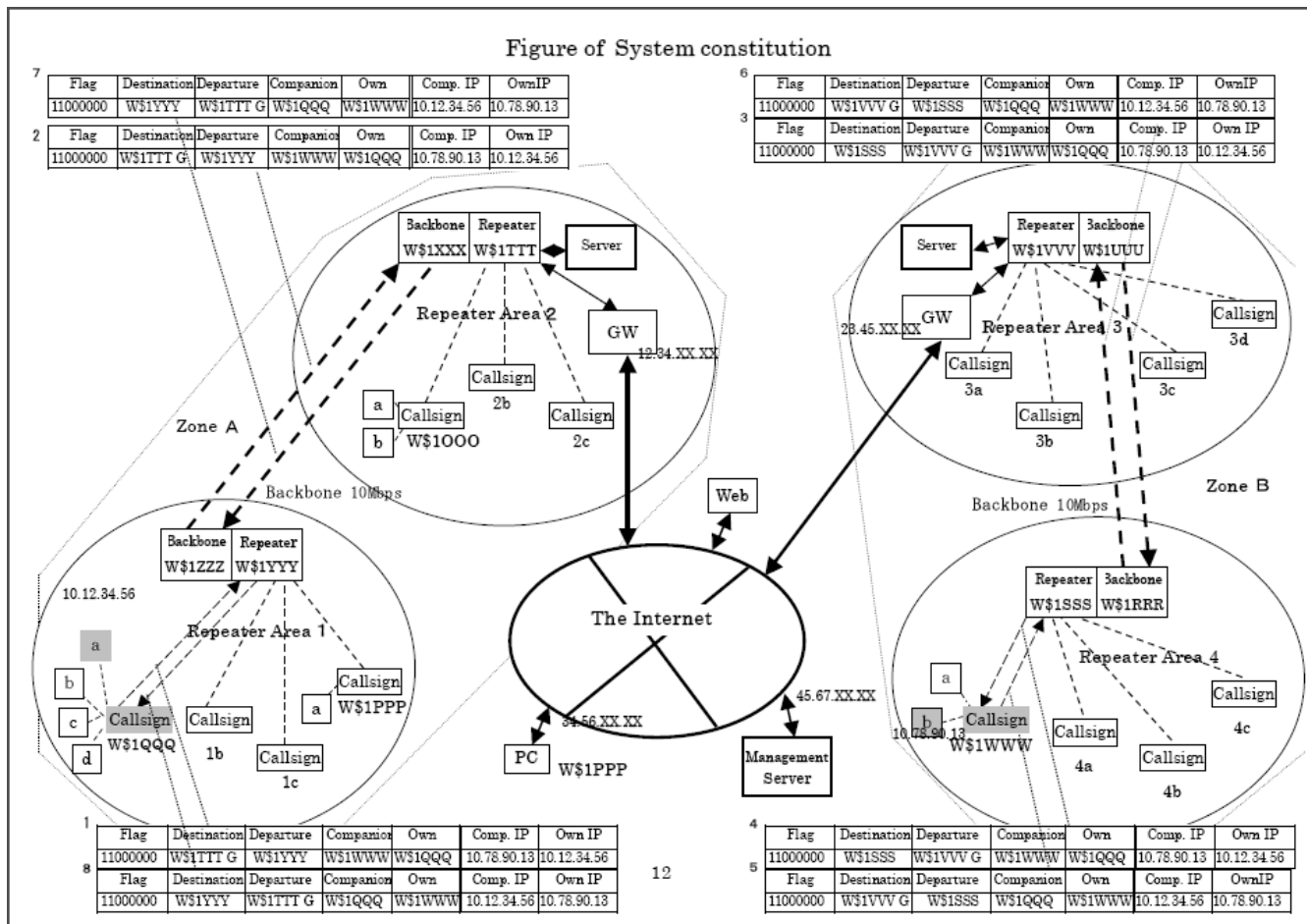
The Comp. IP and Own IP are shown for reference if this was a DD communications. As they do not change and are not passed as part of the D-STAR protocol, they can safely be ignored for the purposes of the following explanation.

Headers 1 through 4 are W$1QQQ calling W$1WWW. Headers 5 through 8 are W$1WWW calling W$1QQQ. Note that "Own Callsign" and "Companion Callsign" are never altered in either sequence. The "Destination Repeater Callsign" and the "Departure Repeater Callsign" are changed between the gateways. This is so the receiving gateway and repeater controller know which repeater to send the bit stream to. It also makes it easy to create a "One Touch" response as Icom has done by simply placing the received "Own Callsign" in the transmitted "Companion Callsign", the received "Destination Repeater Callsign" in the transmitted "Departure Repeater Callsign", and the received "Departure Repeater Callsign" in the transmitted "Destination Repeater Callsign".

Use of the "special" character '/' at the beginning of a callsign indicates that the transmission is to be routed to the repeater specified immediately following the slash. For instance, entering "/K5TIT B" in the "Companion Callsign" would cause the transmission to be routed to the "K5TIT B" repeater for broadcast. Using the above example, W$1QQQ would put "/W$1SSS " in the "Companion Callsign" for the same sequence 1 through 4 to occur. At the W$1VVV gateway, however, the "/W$1SSS " in the "Companion Callsign" would be changed to "CQCQCQ ". All stations within range of W$1SSS would see the transmission as originating from W$1QQQ and going to CQCQCQ just like that station was local (but the "Departure Repeater Callsign" would be "W$1VVV G" and the "Destination Repeater

Callsign" would be "W$1SSS "). Replying would still be done the same way as before since the received "Companion Callsign" is ignored when programming the radio to reply.

Every "terminal" (station) has an IP address assigned to it for DD purposes. The address is assigned from the 10.0.0.0/8 address range. The D-STAR gateway is always 10.0.0.2. The router to the Internet is always 10.0.0.1. The addresses 10.0.0.3-31 are reserved for local-to-the-gateway (not routable) use. What this makes possible is the ability to send Ethernet packets to another station by only knowing that terminal's IP address and the remote station can directly respond based solely on IP address. This is because the gateway software can correlate IP address with callsign and ID. This makes it possible to route DD Ethernet packets based on the "Companion Callsign" or based on IP address with "Companion Callsign" set to "CQCQCQ ".

Key points of D-STAR routing:

1. Simplex uses only "Own Callsign" and "Companion Callsign". The repeater callsigns are set to spaces. "CQCQCQ " is the universal "calling everyone" callsign and ID for the "Companion Callsign" only.
2. Local repeater use sets only the "Departure Repeater Callsign" repeater. "Destination Repeater Callsign" is set to spaces.
3. Accessing the gateway requires the local repeater in "Departure Repeater Callsign" and the local gateway in "Destination Repeater Callsign".
4. Routing outside of the local zone requires programming the radio to access the gateway.
5. Inter-zone and inter-area routing by station callsign and ID requires the radio to be programmed to access the gateway.
6. Inter-zone and inter-area routing using the slash with a repeater callsign and ID requires the radio to be programmed to access the gateway.
7. DD routing based on assigned 10.0.0.0/8 IP address requires the radio to be programmed to access the gateway.
8. Routing is unidirectional. Responding station(s) must program their radios correctly to reach the calling station.
    a. D-STAR routing is not linking, it is routing of the bit stream from source to destination.
    b. Responding requires proper configuration of the responding radio.

Icom Enhancements

The D-STAR specification defines the protocols and general network architecture. It is left to the manufacturers (including independent developers) to refine this into an operational model. As Icom is the first manufacturer of D-STAR radios and software, they have had a significant amount of flexibility in their implementation.

On the RF side, the data frame content in the DV protocol is generally undefined (every 21st frame and the last frame are reserved). This is the only opportunity for customization of the RF signal in the specification that does not have to be forced compatible with other radios and software. Icom has made use of it for 3 different and distinct functions which are "hidden" from each other by a "control" byte occupying the first byte of the 3 byte data frame:

1. Control functions including repeating the RF header periodically to help receiving radios get a valid RF header for informational purposes only when operating under noisy conditions.

2. Repetitive transmission of a 20 character message for display on the receiving radio(s)' front panel. The message is displayed upon reception in a scrolling manner.
3. Passing 8 bit data between data ports on the radios.

#1 is solely used by the radios to recover sending callsign information on a noisy connection. Because it is not defined in the specification, it cannot be used to alter a header that has already been passed. It is very unlikely that these will be received more intact than the original RF header because the data frames do not have forward error correction.

#2 exists to allow a person to put a short announcement message in their transmission. This is not modifiable while transmitting and very difficult to change in-between transmissions.

#3 is usable by any application connected to the serial port on an Icom radio. As indicated, the data on the serial port is not placed into the data frames unaltered. It is transmitted 1 or 2 bytes at a time with the Icom "control" byte occupying the first byte of the data frame. Icom also implemented always-enabled xon/xoff flow control. This precludes the use of those characters in the data stream. Because of bit errors that can be received, it also precludes use of xon/xoff flow control by the attached device as there is no way to know if an xoff is received or issued by the radio. Some radios use the serial port to control the radio by using certain bytes (mostly 0xF0-0xFF) to denote control information. This means that these characters are also off-limits.

Icom makes use of #3 to pass GPS information. Because this information is passed using the #3-type control bytes, it is visible to the serial port on radios not running in GPS mode (GPS modes block the serial port from the data frames). The original GPS format (implemented on all radios that support GPS) is standard NMEA GPS strings with checksums followed by an ASCII line that contains the transmitting callsign, ID, and a duplicate of the 20 character message being sent to the front panel. This line is generated by the transmitting radio and is not interpreted by the receiving radio. GPS-A mode was introduced to provide a more concise and reliable position representation. GPS-A mode consists of a single APRS format line prefixed by a CRC.

It is important to remember that all uses of the data frames are not protected from bit errors nor do they have any indication of bit errors. In the case of #1, the RF header contains a CRC for validation. #2 has no validation. Validation with #3 is left to the connected applications.

The other area open for significant customization is the gateway operation and the gateway-to-gateway communications. The latter may be addressed in a future addition to the D-STAR specification. However, it was never the intention of the JARL to dictate how software or devices operate so gateway operation will be left to the manufacturers and independent developers.

The Icom gateway software is currently at version 2 released this year. Version 1 was based on a mesh network design where all gateways communicate directly with all other gateways. Specifically, when one gateway's table(s) gets updated, that gateway contacts all other gateways with the new information. While this works well with small gateway networks, it became obvious that it would not be supportable with the explosive growth experienced in the world-wide D-STAR network. To meet the growth requirements of the new D-STAR network, Icom introduced G2 (Gateway Version 2) earlier this year.

G2 is designed around a hub and spoke topology for information exchange but maintaining the basic D-STAR communications architecture where DV and DD communications occur directly between the gateways. Gateways exchange information with the central Trust Server regarding their callsign (zone call), Internet IP address, connected area repeaters, and recent activity on the area repeaters. This

46

information is mentioned in generalities in the D-STAR specification but the actual data interchange format is not defined. To accomplish the allocation of 10.0.0.0/8 addresses for individual stations, the G2 software automatically reserves 8 addresses for each callsign registered through the gateway registration software. Each registered user can designate which ID is assigned to the specific IP address and also a DNS name in the dstar.local domain. This information is also exchanged with the central Trust Server. The IP address groups are obtained from the Trust Server so there is no duplication in the network. The central Trust Server then broadcasts the information received from individual gateways to all of the gateways so they can quickly determine which gateway a user or repeater is connected to and the Internet IP address of that gateway.

One final note on the G2 gateway: due to a programming restriction in station registration form, G2 restricts the ID character (8th character of callsign) to a space or upper-case alphabetic (no numbers). This restriction is specific to the G2 software, not to the D-STAR specification.

Independent Enhancements

In addition to Icom, there have been other developers create applications for the D-STAR systems. Icom's adherence to the D-STAR specification has lead to DStarMonitor which monitors the repeater/gateway communications and parses the information into database entries and parses the Icom "serial port" data to a TCP port for use by an application just like the application would work connected to a radio monitoring the repeater frequency.

DPlus is a multifaceted application that runs on the gateway PC. It also monitors the repeater/gateway communications and provides enhanced features like echo, prerecorded announcements, DV reflectors, etc.

D-PRS is a translation specification for the Icom GPS information to APRS format and to use the Icom serial data port for reliable transport of APRS packets between APRS clients.

Other applications tend to concentrate on the Icom serial port. These include messaging, form completion, and small file transfer.

There are independent gateway projects underway at the time of writing of this paper. Further information may be available for presentation at DCC 2008.

Conclusion

The D-STAR specification is a focused definition of 2 RF digital protocols: digital voice and digital data. It also defines the control information contained in every transmission and the network architecture that control information supports. Finally, it defines the repeater/gateway communications protocol to ensure compatibility across platforms between gateways and repeaters.

Digital voice (DV) is a protocol designed to convey audio information. Because of its design, there is limited bandwidth for very low speed data to accompany the audio information. Icom has made available a serial port to utilize a subset of that low speed data bandwidth by applications attached to the radios. Icom uses this same subset of low speed data bandwidth to convey GPS information to remote radios.

Digital data (DD) is a protocol designed to convey Ethernet packets. Implied D-STAR network design designates the 10.0.0.0/8 IP address range for use to connect network devices via the DD protocol. The DD protocol is not limited to IP packets although extra features are available to IP packets.

The D-STAR specification defines the repeater/gateway IP communications to facilitate multiple repeater or gateway platforms. This portion of the specification reinforces the overall network architecture mentioned elsewhere in the specification. The specification purposely does not define how any function such as the gateway operates. Only the communication between entities is defined in the specification. The gateway/gateway communication is yet to be included at the time of the writing of this paper.

The D-STAR network architecture is purely based on callsign and station ID. The callsign and ID applies to individual stations, repeaters, and gateways. All routing is handled within the gateways. The user only needs to know who they want to talk to and what the callsign and ID is of the local repeater.

D-STAR brings true world-wide station-to-station communication capabilities to amateur radio.

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[i] D-STAR® is a registered trademark of the Icom Incorporated Corporation Japan