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HF RADIO DATA COMMUNICATION

*CW to CLOVER**

Amateur radio operators have been engaged in data communications since the first days of spark gap transmitters. In fact, the first and ONLY means of early radio communications required ON/OFF keying of the radio transmitter using a digital code. That code was, of course, the Morse code. With the invention of amplifiers and voice modulators, some amateurs "strayed" into nondigital modes (AM, SSB, etc.). However, amateur radio has seen a resurgence of interest in digital modulation, and there are now many of us using RTTY, AMTOR, packet, and CW. In this article, we'll discuss these popular digital modes, along with a new one called "CLOVER."

Digital modes

Morse code

Morse code is the original data communications code used by amateur radio operators. Often abbreviated as CW (continuous wave), Morse code is transmitted by ON/OFF keying of the transmitter carrier. Combinations of dots and dashes (short and long key-down times) make up the character codes. Morse code is unique among digital codes in that the length of time required to send each character varies with the character sent. For instance, E is one dot, while zero is five dashes. An E is sent in 1/10th the time required to send zero. Morse is a very efficient code for sending English language text because the most frequently used characters are assigned the shortest code combinations (E, I, S, T, A, N). Morse code is relatively easy to learn, and requires only a key and a skilled operator. It is designed for manual operation.

However, the varying time length of each Morse character and the ON/OFF carrier keying used to send Morse code, make automatic reception of Morse code by computers a very difficult task. Automatic computer Morse code decoders have been designed, and Morse receive algorithms improve with each generation. However, automatic Morse decoding still is not equal to the decoding skills of a good CW operator.

It must also be noted that the abbreviation CW in reference to Morse code transmission has helped perpetuate a myth that survives to this day: "Morse code is the most bandwidth-efficient mode of communications," and "CW has no bandwidth at all." As can be seen in **Figure 1**, this is by no means the case! **Figure 1** shows the frequency spectra generated by a 60-WPM CW transmitter using the ARRL-approved rise and fall times (5 ms). Morse code is obviously not a "zero-bandwidth" emission![1]

RTTY

RTTY (radio teletype), the successor to Morse code, was originally developed to automate wire-line message communications. Very complicated teletype machines allowed automation of message handling. Some of us still use these "mechanical computers." As a result of military requirements during World War II, teletype ma-

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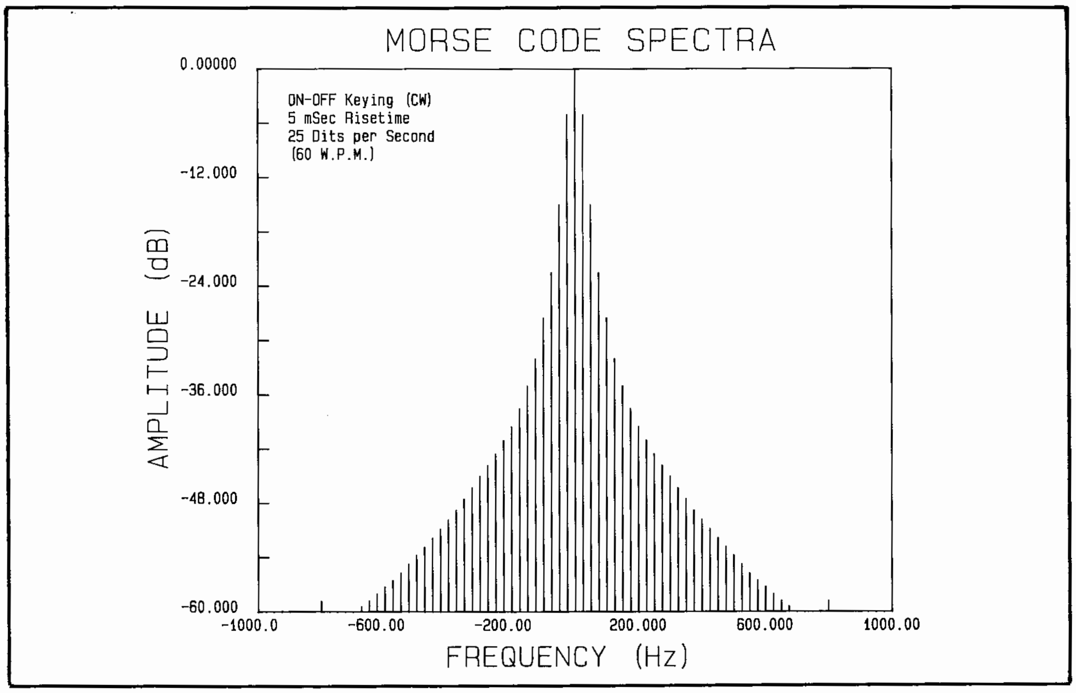

Figure 1. Morse code spectra.

chines were connected to radio transmitters and RTTY came into being. Amateur RTTY today still follows the general techniques first used in the 1940s (but with notable improvements in terminals and modems).[2,3]

Most amateur RTTY operators use the original five-bit "Baudot" (or "Murray") code. The five bit code length limits Baudot to a maximum of 32 unique characters—not enough to represent 26 letters, 10 numbers, and punctuation. This problem is solved by use of LTRS and FIGS case-shift characters; each code combination is used twice. However, Baudot can't be used to send lower-case letters or an extensive set of control characters.

In 1980, United States amateurs were allowed to use the seven-bit computer ASCII code as well.* This code is used in all modern computers and allows unique encoding of 128 different letter, number, punctuation, and control characters. Many of us experimented with ASCII, and soon learned that it's not very robust when used on HF. Noise and QRM "hits" often convert a valid character into a control code that wreaks havoc with our printers (large/small type, form-feeds, etc). Most RTTY amateurs continue to use the Baudot code.

Baudot and ASCII are both "asynchronous" codes. They have START and STOP pulses that allow receive synchronization on each character. Other data modes use codes that are "synchronous." They have no START or STOP pulses.

Amateur RTTY can be used at many "speeds," but 45 baud (60 WPM) and 75 baud (100 WPM) are by far the most popular.** When ASCII is used on HF, it's almost always sent at 110 baud (100 WPM). These speeds correspond to a data "throughput rate" of 6 to 10 characters-per-second (cps). RTTY modes offer no means to correct transmission errors.

HF RTTY is transmitted using Frequency Shift Keying (FSK) of the transmitter radio frequency. This can be done by either shifting a transmitter oscillator directly, or by driving an LSB transmitter with audio tones. Most of the modern transceivers that include an "FSK" mode really use an internal audio oscillator to drive LSB transmitter circuits. The standard RTTY "SHIFT" is 170 Hz—the difference between the MARK

*There is more than a little confusion as to whether ASCII is a seven-bit or eight-bit code. When sending ASCII on HF at 110 baud, most terminals send seven data bits and one "parity" bit. There are eight bits between the Start and Stop pulses. One-hundred and ten baud ASCII usually has one start bit, eight "data field bits," and two stop bits, for a total length of 11 bit units. However, this is by no means "standard." Some systems send only seven data bits and no pulse where the parity bit is normally located. If an eight-bit generator sets bit 8 to MARK, the serial asynchronous code will be compatible with receiving UARTs set for either seven-bit or eight-bit codes (bit 8 set to "always MARK").

**For FSK RTTY, AMTOR, and packet radio, the baud rate is equal to 1 divided by the time width of one data pulse. For example, 60-WPM RTTY has a data pulse width of 22 ms. Its baud rate is 1/0.022 = 45.45 baud, usually abbreviated as 45 baud. However, CLOVER has the capability of sending more than one data state per data pulse, by using multiple phase and amplitude levels. Therefore, CLOVER has one baud rate—31.25 baud per tone pulse (125 baud composite)—but several throughput rates—18.75 bits-per-second (bps) to 750 bps.

and SPACE frequencies. Most HF RTTY demodulators use audio tones at 2125 (MARK) and 2295 Hz (SPACE). RTTY demodulators come in many different shapes and price ranges. High performance demodulators can be very complicated—and expensive.[4,5]

RTTY has proven to be a convenient and popular mode for most of us. In addition to its wide use for rag chewing and chasing DX, RTTY made a new service possible—"mailbox" store-and-forward message handling (MSOs). However because neither Baudot nor ASCII RTTY include error correction, other modes like AMTOR, packet, and CLOVER are more suited for mailbox use.

AMTOR

AMTOR is an amateur adaptation by G3PLX of a commercial RTTY mode first devised in the late 1950s for ship-to-shore use. The commercial version is often called TOR (Teleprinting Over Radio) or SITOR (Simplex Teleprinting Over Radio). The CCIR and FCC call it Direct Printing Radiotelegraph. AMTOR specifications are defined in CCIR 476-4 and CCIR 625. AMTOR adds one mode not described by the CCIR—the "Monitor" or "Listen" mode.[6-13]

Like RTTY, HF AMTOR uses simple FSK transmitter modulation with 170-Hz shift. Commercial SITOR also uses 170-Hz shift FSK modulation, but with reverse data polarity. AMTOR signals are always sent at a data rate of 100 baud.

AMTOR digital code has seven bits. The AMTOR code is arranged so all characters contain four MARK and three SPACE data pulses (called "B" and "Y" pulses in "AMTOR-speak"). The receiving code converter examines each character for this 4/3 ratio and assumes that the character is in error if the ratio test fails. This is the error detection algorithm of AMTOR.

AMTOR has two primary operating modes: ARQ (Automatic Repeat reQuest) and FEC (Forward Error Correction). In ARQ mode, the sending station sends a burst (or "chirp") of three characters and turns its transmitter OFF. The receiving station examines each character for the 4/3 bit ratio. If all three characters have the correct ratio, the receiving station sends a short control signal that means "send next chirp." If any of the three characters fail the 4/3 ratio test, the receiving station sends a different control code that means "repeat last chirp."

Note that in ARQ mode, both transmitters chirp ON and OFF, but data is sent in one direction only. The station sending data is called the ISS (Information Sending Station) and the station receiving text the IRS (Information Receiving Station). Data always flows from the ISS to the IRS. However, a special OVER command reverses the roles of the two stations so data may be passed in either direction. ARQ mode only works in a two-station network. Three or more stations may not use ARQ mode with full error correction. Additional stations may, however, Monitor, but without error correction.

ARQ stations are time synchronized so the transmitting time of one corresponds to the receiving time of the other. AMTOR is also a "synchronous" rather than "asynchronous" mode. AMTOR characters do not include START and STOP pulses. Accurate timing is important in AMTOR and, for this reason, AMTOR controllers must be considerably more sophisticated than RTTY decoder devices. To assure correct timing, the station making the original call is named the MASTER station. It sets the timing for both stations for the duration of the ARQ "link." The station originally called is the SLAVE station.

AMTOR ARQ mode uses station identifier SELCAL characters (SELective CALl). An ARQ mode link is initiated by the MASTER station that sends the SELCAL of the desired station. When a receiving station recognizes its SELCAL code, it responds with a chirp and the link is established. Note that only the designated station will respond, and many stations may listen on the same frequency. A CCIR-476 link requires only the SELCAL of the destination station; a CCIR-625 link exchanges the SELCAL of both stations. The CCIR-625 SELCAL code is also longer—seven characters rather than four for CCIR-476. Both CCIR-476 and CCIR-625 formats are legal for U.S. amateur use, but most of us continue to use CCIR-476 SELCAL codes. A special control END character is used to terminate an AMTOR ARQ transmission.

AMTOR FEC transmissions are one-way and may be received and printed by any AMTOR-equipped station monitoring the frequency. A SELCAL isn't used in FEC mode. Amateurs use FEC mode primarily for calling CQ, but sometimes also for round-table rag-chewing.

FEC mode is much like RTTY in that one station sends his complete message and then turns his transmitter OFF to receive the other station(s). FEC mode does not use three-character chirps or repeat/continue control signals from the receiving station. FEC mode provides limited error correction by sending every character twice. The repeat of each character is spaced in time so a character lost by a noise or interference burst may be received correctly at a later time. The receiving AMTOR controller examines the first received character for the 4/3 ratio and prints it when the ratio passes. If the first transmission of a character fails the test, the second transmission of that character is examined and printed if it is correct. If both transmissions of a character fail, a blank space (or underline) is printed to indicate an uncorrectable transmission error.

FEC mode isn't as "robust" as ARQ mode, and some errors can't be corrected. However, FEC mode does allow transmission to more than one other station with some means of error correction.

Selective FEC (SEL FEC) is a third mode used in commercial SITOR. This mode requires a SELCAL code, much like ARQ mode, and will only be received by stations whose SEL-FEC SELCAL matches that sent by the transmitting station. SEL-FEC is commonly used by commercial land stations to restrict transmissions to "company ships." The ARQ SELCAL and SEL-FEC SELCAL are usually different sets of characters. To date, most amateurs haven't used SEL-FEC mode.

AMTOR and SITOR enjoy widespread use all over the world, and the benefits of error detection and correction are greatly appreciated. The APLink program developed by W5SMM is widely used to link HF AMTOR to VHF packet message networks. As will be discussed later, AMTOR is considerably more reliable for HF data transmission than packet radio.

However, AMTOR is not without its limitations. AMTOR uses an error detection code, but the code is not infallible. In fact, a burst error can frequently change the states of not only one but two data bits—resulting in the printing of incorrect characters. This happens infrequently, but it does happen.

Also, the AMTOR throughput speed is very slow by modern data standards. If there are no errors to be corrected in ARQ mode, the maximum rate at which data can be transmitted is 6.67 characters per second (cps). This is about 66 WPM, or the equivalent of 50-baud RTTY. When errors are detected and must be corrected by retransmission, this rate slows down. AMTOR, therefore, is not a rapid way to send a lot of data.

Finally, due to the unique 4/3 ratio encoding of the seven-bit characters, the AMTOR code supports a maximum of only 36 unique code combinations, including control signals. AMTOR uses the same algorithm as Baudot, and each bit combination is used twice: once in LTRS case and again in FIGS case. AMTOR, therefore, suffers the same problems as Baudot for transmission of lower-case letters and computer codes. This isn't normally a serious limitation for ship-to-shore commercial use, or in most amateur applications. However, it is a big handicap if computer data is to be sent.*

AMTOR, like RTTY and CW, is a fairly narrow-bandwidth emission. The measured spectrum of an AMTOR modulator (ARQ-1000 and ST-8000) is shown in **Figure 2**.** This spectrum is also representative of that produced by a RTTY station (45 baud is slightly narrower). Due to sidebands and demodulator filter bandwidths, AMTOR stations can be operated with a minimum of 1 kHz spacing between signals if all stations use 500-Hz wide receiver filters.

PACTOR

PACTOR is a new development from DL6MAA, DF4KV, DL1ZAM, and DL3FCJ. At this time, only a few PACTOR units have found their way into the United States, and some features of the new mode are still under development. PACTOR is a modification of AMTOR that provides moderate speed improvements over AMTOR. PACTOR uses an ASCII character set rather than Baudot, and error detection is by means of a CRC (Cyclic Redundancy Check) much like that used for AX.25 packet radio. PACTOR also includes an optional data compression mode that can further increase the data speed. However, the compression algorithm (Huffman encoding) is language specific; it works great on text in some languages, but won't increase speed on nontext data transmissions. Finally, PACTOR includes a speed-change algorithm in which the bit rate of the data may be increased from 100 baud to 200 baud when few errors are detected

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*W5SMM and G3PLX are now experimenting with an extended AMTOR code that supports upper and lower case letters.

The spectra shown in **Figure 2 is a plot of measured data taken from the audio output of a HAL ST-8000 and ARQ-1000 operating in ARQ mode (170-Hz shift, tones = 2125/2295 Hz). The data has been numerically shifted to show 0 Hz as the center frequency and 0 dB as the maximum peak amplitude. The measurement device was a Hewlett-Packard Model HP-3561A Dynamic Signal Analyzer. The spectra of a 60-WPM (45 baud) FSK RTTY signal will be similar, but the MARK and SPACE spectra will be slightly narrower.

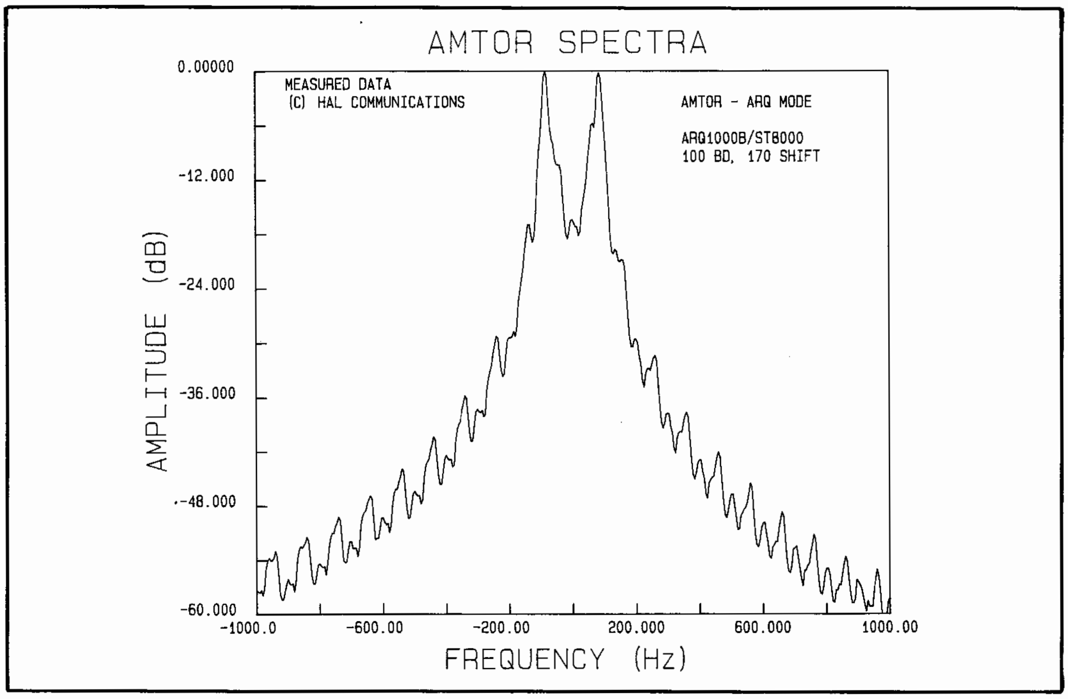

Figure 2. Amtor spectra.

(good conditions). PACTOR is still experimental and promises moderate gains in data throughput on HF radio—two times if 200 baud can be used, and also up to two times when Huffman data compression can be used. PACTOR, like AMTOR and RTTY, uses 170-Hz shift FSK modulation.[14,15]

As with AMTOR ARQ mode, PACTOR is an error detection and repeat mode, rather than a true error correction mode (without requiring repeats). At this time, PACTOR is an interesting new mode that holds good promise for modest improvements in HF data transmission over that presently offered by AMTOR.

Packet radio

Packet radio has truly caused a revolution in amateur radio digital mode operations, thanks to pioneering work by TAPR (Tucson Amateur Packet Radio group). Packet radio uses a modification of the ANSI X.25 protocol—AX.25.[16-20]

Like AMTOR, packet data is sent in bursts called "data packets." Unlike AMTOR, data is encoded in eight-bit "bytes," and the ASCII code may be sent and received directly (as well as eight-bit binary data). The start of a packet includes callsign identifiers and allows specification of repeater paths. The data packet ends with a CRC check sum number (Cyclic Redundancy Check). The receiving station computes a CRC number from the packet data it has received, compares that to the CRC sent, and requests a repeat if the two do not match. This is much the same as AMTOR ARQ mode and, in fact, packet radio is another form of the generic ARQ class of data transmission modes. Also like AMTOR, packet includes station identifiers, and links only with designated stations. However, these identifiers can be complete callsigns.

Unlike AMTOR, packets contain many bytes or characters—32, 64, and 80 are common numbers in use—and may have up to 255 bytes per packet. Packet radio burst transmissions aren't evenly spaced in time; packet transmissions are randomly spaced. At present, packet radio uses CSMA (Carrier Sense, Multiple Access): the controller listens and does not transmit if other stations are already sending. CSMA allows many packet radio stations to share the same frequency—each responding only to the station with which it is linked. This feature was a large boon to early development of VHF packet radio, but has proven to be a major limitation now that thousands of hams are using the mode. If a lot of stations (10 or more) attempt to use the same frequency, all traffic slows and eventually bogs down completely. On HF, it takes only three or four stations to gridlock the channel.

Packet radio has become almost the exclusive data mode used on VHF. Typical 2-meter VHF FM packet stations use 1200-baud, 1000-Hz shift AFSK modems based on the Bell 202 modem standard (1200/2200 Hz). A growing number of VHF and UHF packet operations are now switching to 2400-baud PSK modulation. A few UHF packet network relay stations operate at very high data rates.

Packet radio has also been attempted on high frequencies, using 300-baud, 200-Hz shift FSK modulation. HF packet radio hasn't been a big success, and most of the problems may be traced to the modulation format and to the AX.25 protocol itself.

The modulation format used for HF packet is based on the Bell 103 300-baud telephone line modem. While this format is well suited for stable low-noise wire lines (and VHF radio), it has serious problems for HF use. First, use of simple FSK at a 300-baud data rate flies in the face of years of evidence that ionospheric multipath distortion severely affects any modulation in which the base modulation rate exceeds 100 to 150 baud. Multipath time "smearing" often exceeds 3 to 5 milliseconds. Since the width of a 300-baud data pulse is only 3.3 ms, time smearing irretrievably masks data bits. Second, use of the 300 baud rate with a very narrow FSK shift (200 Hz) creates a spectrum that is not easily detected. In fact, traditional in-band diversity from separate filters for MARK and SPACE, like those used for RTTY and AMTOR, is not possible. In retrospect, it can be stated that the choice of narrow shift FSK and a 300-baud data rate for HF packet was a poor engineering decision.

The AX.25 protocol is excellent for wireline and VHF radio use. However, the very features that make the protocol so useful on VHF, conspire to create big problems for HF use of AX.25. First, packets are loaded with a lot of "overhead"—non data characters (callsigns and repeater fields, for example). Second, packet radio is an error detection mode, not a direct error correction mode. The CRC is computed for the entire packet (including overhead). If the received CRC doesn't match that transmitted, the entire packet must be repeated.

Packet lengths can be set as short as 32 characters, but this is very inefficient. Often there are more overhead than data characters in a short packet. We would much rather send longer packets (64, 80, or greater) and improve the efficiency. Sending longer packets increases the time the transmitter is on the air and, more importantly, the time over which the CRC is computed, and the time during which completely accurate data must be received.

HF ionosphere disturbances are often of a "burst" nature—short, high intensity, and widely spaced. One "burst" within a packet requires the repeat of the complete packet. As the packet length is increased to improve efficiency, the probability of damage by a burst greatly increases to the state that no data can be passed. We, therefore, have the contradiction that short packets should be used to combat burst interference and noise, but that long packets give better efficiency. The ultimate result in both con-

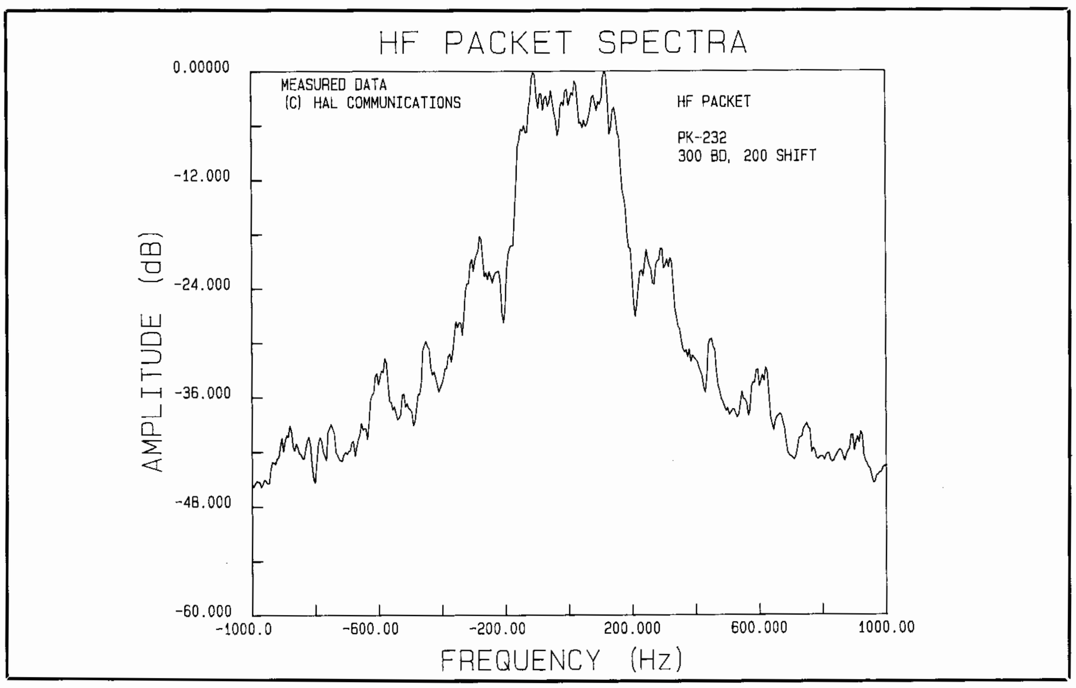

Figure 3. HF packet spectra.

ditions (long or short packets) adds up to very slow transmission of data. HF packet throughput can be as high as 15 to 20 characters-per-second at 300 baud under ideal conditions. However, what is actually observed are throughputs on the order of two to four characters-per-second—less than AMTOR, which operates at 1/3 the baud rate and in a narrower bandwidth!

Further, the "CSMA" concept doesn't work well on HF. It is easily tricked by noise bursts and splatter from other HF packet signals. Also, CSMA doesn't prevent simultaneous transmissions by multiple stations (collisions) due to propagation skip zones—the "hidden transmitter effect" (that is, your station can't hear the interfering station but your destination station can).

HF packet radio at 300 baud, 200 Hz shift is very spectrum inefficient. **Figure 3*** shows the measured spectrum of an HF packet modulator (PK-232). The "gentlemen's agreement" is that all HF packet stations must be spaced by at least 2 kHz to avoid mutual interference. This interference is caused by the wide bandwidth of the modulation sidebands themselves and the poor selectivity requirements forced on the receive modem by the FSK modulation format (300 baud/200 Hz shift). Two AMTOR stations can operate without interference in the spectrum required for one HF packet station. As we shall see, CLOVER allows four stations to operate in the same bandwidth as an HF packet signal.

In summary, we must comment that while packet radio is a wonderful VHF and UHF mode, it has very basic limitations for HF use. Practically all aspects of today's HF packet signal are wrong for the conditions radio operators face daily on HF radio circuits.

CLOVER

CLOVER is a new data mode invented by Ray Petit, W7GHM. Ray's work was inspired, first, by his earlier development and experience with very narrow bandwidth coherent CW and then by his observation of the many HF packet radio problems we've discussed. Rather than modifying existing modes, the CLOVER design started with a careful analysis of the unique problems of sending data via HF radio. CLOVER is tailored to overcome HF radio's unique problems.[21-25]

There are two variations of CLOVER: CLOVER-I is a 100-Hz bandwidth mode;[22] CLOVER-II is a 500-Hz bandwidth mode. The CLOVER-I waveform is a steady sequence of smoothly shaped pulses at a single carrier frequency. Data is sent in the difference in the phase between successive pulses. The base data rate of CLOVER-I is 25 bits per $\log_2$ PSK level per second. Ray uses shaping of the time pulse to reduce all CLOVER sidebands to less than -60 dB beyond the 100 Hz bandwidth. CLOVER-I requires relatively simple analog circuits in the modem, but it makes extreme requirements on the radio equipment. In CLOVER-I, the radio frequency stability and tuning accuracy must be maintained within $\pm$-0.10 Hz! Because this is not achievable by most commercial transmitters or receivers presently available, part of the CLOVER-I design includes the transceiver itself.

CLOVER-II is a much expanded version of CLOVER-I.[24] This mode makes heavy use of digital signal processing (DSP) techniques. CLOVER-II bandwidth is expanded to 500 Hz to better match the "narrow" filters commonly available for modern commercial transceivers. The CLOVER-II "carrier" is a steady sequence of four tone pulses at ascending audio frequencies. Each pulse has a duration of 32 milliseconds; successive pulses reach their peaks at instants 8 ms apart. The four tone pulses are also spaced 125 Hz apart in frequency, and carefully shaped in amplitude so that their spectra don't overlap. Data is carried in the difference between phase and/or amplitude of successive pulses at the same frequency. These changes are made only at the instants midway between the peaks of two successive pulses when their amplitudes are zero. As a consequence, the usual wide bandwidth associated with phase modulation is avoided. The composite signal is 500 Hz wide. The crosstalk between two CLOVER signals spaced 500 Hz apart is less than 50 dB. As with CLOVER-I, varying levels of PSK and ASK modulation are used on each tone pulse so data throughputs as high as 750 bits-per-second are achieved from a base modulation rate of 31.25 bits-per-$\log_2$ (level)-per-second.

CLOVER-II has a total of eight different modulation formats that may be selected. In order of increasing throughput, these are: dual diversity BPSK (Binary PSK), dual diversity FSK, BPSK, QPSK (4-level PSK), 8PSK (8-level PSK), 16PSK (16-level

*The spectra shown in **Figure 3** is a plot of measured data taken from the audio output of an AEA PK-232 operating in HF packet mode with 300 baud data and a shift of 200 Hz (tones = 2110/2310 Hz). The data has been numerically shifted to show 0 Hz as the center frequency and 0 dB as the maximum peak amplitude. The measurement device was a Hewlett-Packard Model HP-3561A Dynamic Signal Analyzer.

CLOVER-II THROUGHPUT

Binary Data Through-put (Bits-per-second)

R-S CODE	EFF	Modulation: 4 x BPSK Base Rate: 31.25 MODE: "BDIV"	2 x "FSK" 31.25 "FDIV"	BPSK 125.00 "2P"	QPSK 250.00 "4P"	8PSK 375.00 "8P"	16PSK 500.00 "16P"	8PSK/2ASK 500.00 "8P2A"	16PSK/4ASK 750.00 "16P4A"
"60"	60%	18.75	18.75	75.00	150.00	225.00	300.00	300.00	450.00
"75"	75%	23.44	23.44	93.75	187.50	281.25	375.00	375.00	562.50
"90"	90%	28.13	28.13	112.50	225.00	337.50	450.00	450.00	675.00
"100"	100%	31.25	31.25	125.00	250.00	375.00	500.00	500.00	750.00

COMPARISON HF DATA MODES

RATE	COMMON NAME	Usable Data Bits	|- HF Data Throughput -| MAXIMUM CPS/bps	TYPICAL CPS/bps	ERROR CORRECT	HF SUITABILITY
45 BD	"60 WPM" RTTY	5 bits	6/30	*	None	GOOD, Few Errors
75 BD	"100 WPM" RTTY	5 bits	10/50	*	None	GOOD, Some Errors
110 BD	"100 WPM" ASCII	7 bits	10/70	*	None	FAIR, Many Errors
300 BD	"300 BAUD" ASCII	7 bits	30/210	*	None	VERY BAD, All Errors
100 BD	"AMTOR/SITOR"	5 bits	6.67/50	6/30	Yes	VERY GOOD, No Errors
300 BD	"HF PACKET"	8 bits	20/160	2/16 - 4/32	Yes	POOR, Many Repeats
1200 BD	"VHF PACKET"	8 bits	80/640	0/0	Yes	VERY BAD, No Data

* = No error correction, reception of good or bad data is at constant rate
CPS = Characters-Per-Second Data Throughput
bps = Bits-Per-Second Data Throughput

Table 1. Typical data throughput rates of the various combinations of CLOVER modes and codes.

PSK), 8PSK/ASK (8PSK plus 2-level ASK), and 16PSK/4ASK (16PSK plus 4-level ASK). As might be expected, the data throughput increases with the complexity of the modulation, and much better ionosphere conditions are required for the complex modes. Typical data throughput rates of the various combinations of CLOVER modes and codes are shown in **Table 1.**

CLOVER-II also includes self-adapting software that can adjust for frequency drift and tuning inaccuracies. CLOVER-II requires frequency resolution of ±10 Hz and will track variations up to ±25 Hz, achiev-

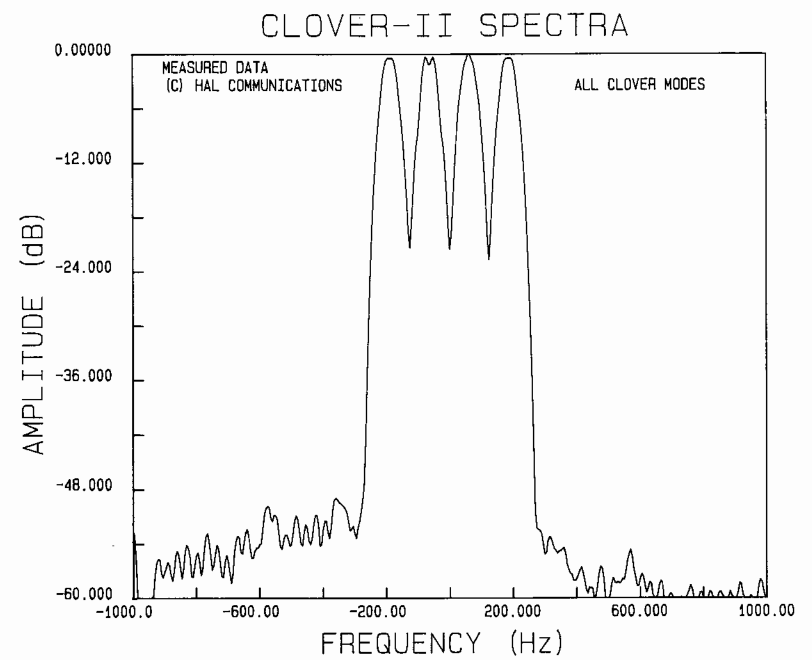

Figure 4. CLOVER-II spectra.

able in most modern HF transceivers. The CLOVER-II frequency spectra is shown in **Figure 4.***

CLOVER ARQ mode is also automatically adaptive. Ionospheric conditions are measured and the data mode of the sending station is adjusted to produce the highest throughput possible at the current conditions. As previously noted, CLOVER has eight modulation modes, four Reed-Solomon encoder modes and four data block lengths—a total of 128 different and unique combinations. These combinations provide great freedom for adaptive adjustment in small increments. The CLOVER demodulation system dynamically and continuously measures key received signal-to-noise ratio (S/N), frequency dispersion, and time dispersion. Thus, the adaptive protocol can determine with a great deal of accuracy which parameter should be changed to optimize data transmission.

Another unique feature of CLOVER-II is Reed-Solomon error correction encoding. This differs notably from that used for AMTOR ARQ and packet radio. AMTOR uses parity coding (4/3 bit ratio) and packet a check-sum (CRC) so the receiving station can detect errors and request repeats. CLOVER's Reed- Solomon encoding allows the receiving station to fix errors without requiring repeat transmissions. This greatly increases the efficiency of CLOVER compared to AMTOR or packet. Of course, there are limits to the capability of in-code error correction and CLOVER will also revert to requesting repeats (ARQ-style) when its error correction system is overloaded.

One of the variable parameters in CLOVER-II modulation is the length of the block of data sent. This is analogous to packet length. However, in this case, block length and the number of Reed-Solomon correctable errors are proportional—longer blocks can correct more errors without requiring repeat transmissions. As noted in the packet radio discussion, longer block transmissions lead to higher efficiencies—higher data throughput. Thus CLOVER, unlike packet, includes an algorithm that is compatible with sending long blocks of data at high efficiency. Of course, if interference, QRN, or ionosphere distortion is high, the error correction ability of the Reed-Solomon encoding can become "overloaded" and repeats are necessary. Also, if bursts occur frequently, a long block may contain several and also overload the error corrector. Four different Reed-Solomon block lengths are available (17, 51, 85, and 255 8-bit bytes) so the different conditions of burst interference/distortion can be tolerated. Efficiency is, of course, inversely related to block length, and the shorter block lengths will result in lower data throughput (as in packet).

The number of errors which the Reed-Solomon coder can correct is adjustable. For each block length, there are three settings corresponding to a maximum of 20, 12, and 5 percent of the bytes in the block that can be in error without loss of the block. Of course, higher error-correcting capacity requires higher coding overhead. The percentage of the bytes in a block that are DATA bytes ("coder efficiency") for the choices named are 60, 75, and 90 percent, respectively. When conditions are exceptionally good and error correction isn't required, the Reed-Solomon error correction algorithm can be completely bypassed—increasing the efficiency to 100 percent (all bits sent are data bits).

For those who may be wondering how this complex modulation fits Part 97 of the FCC Rules and Regulations, let us assure you that all CLOVER modes are indeed in conformance with existing rules. CLOVER passes only one data stream and is therefore not a "multiplex" modulation format. The CLOVER modulation output is audio tones that are used to drive the input to an SSB transmitter. This is CCIR mode "J2," which is allowed. The CLOVER base data rate is 31.25 bits-per-second—well within the 300-baud maximum HF limitation. The CCIR emission designator for CLOVER-II is "500HJ2DEN."

CLOVER places no restrictions on the alphabet used for sending the data. CLOVER accepts any sequence of bytes for transmission and presents the bytes unmodified at the receiver. This avoids the code-specific problems noted for RTTY and AMTOR.

Like AMTOR, CLOVER-II has two primary modes of operation: ARQ and FEC. Also like AMTOR, CLOVER ARQ mode uses rigorous timing of the data transmissions by the two stations. We call CLOVER ARQ transmissions "twitters." ARQ mode is a two-station link requiring SELCAL (full call sign) exchange when linking. CLOVER FEC mode is a "broadcast" format receivable by many stations.

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*The spectra shown in **Figure 4** is a plot of measured data taken from the audio output of a HAL "CLOVER-II" Modem, a developmental model. The ensemble output was centered at 1000 Hz with individual tone center frequencies of 812.5, 937.5, 1062.5, and 1187.5 Hz. The data has been numerically shifted to show 0 Hz as the center frequency and 0 dB as the maximum peak amplitude. The measurement device was a Hewlett-Packard Model HP-3561A Dynamic Signal Analyzer.

As we write this, the CLOVER mode is still under development and working prototypes are now being tested. To date, on-the-air results have confirmed the theoretical work. On typical HF links, CLOVER passes error-free data at rates 10 times faster than either AMTOR or HF packet. Average HF data throughput on the order of 200 to 300 bps is realistic. When conditions are good, the throughput can be as high as 500 to 600 bps.

Mode comparison

We have discussed a total of six unique modes that may be used for transmission of HF data (CW, RTTY, AMTOR, PACTOR, PACKET, and CLOVER). In the sections that follow, we'll compare the performance of these modes.

Data throughput

Table 1 shows typical data rates and character throughout that can be expected from the various HF data modes.

Typical amateur CW speeds are 20 WPM or slower—a throughput of about 2 characters-per-second. Some operators can send and receive code at speeds of 60 WPM and higher, but this is the exception. Also, CW generally requires manual decoding and there is no "automatic" error correction.

RTTY is typically run at 45 baud (60 WPM), but some MSOs operate at 75 baud (100 WPM). At best, RTTY throughput is 10 characters-per-second. None of the RTTY modes offer error correction.

AMTOR, at best, has a throughput of 6.67 characters-per-second, and slows as errors and repeats increase. AMTOR does include error detection, and most receive errors can be corrected and fixed by repeat transmissions. AMTOR ARQ throughput of 5 cps is probably the "typical" condition.

PACTOR offers some improvements over AMTOR: up to 13 cps with 200-baud data rate, and even twice that when data compression is fully active. However, as noted earlier, sending data at 200 baud using simple FSK on HF is risky business and the data compression algorithm will generally not produce a full 2 times speed increase. PACTOR remains to be tested, but the "typical" throughput may be on the order of 10 cps.

As we've noted, HF packet has many problems. As it is now used, the long-time average data throughput of 20-meter HF packet stations is on the order of 4 characters-per-second—often, even less.

Like PACTOR, CLOVER is an experimental mode. Early tests have produced error corrected data throughput at 50 cps in typical conditions, and higher levels in good conditions. To date, CLOVER promises at least a 10 times increase in data throughput over AMTOR or HF Packet.

Error processing

Neither CW nor RTTY has any provision for automatic error detection and/or correction. The human mind is a great "interpreter," and often we can "fill in the blanks." This is fine for chit-chat, but is totally useless for transmitting nontextual data.

AMTOR ARQ mode offers error detection and correction by means of repeat transmissions. However the seven-bit "parity" detection scheme isn't infallible, and AMTOR can print incorrect characters. AMTOR FEC mode also offers limited error correction by sending each character twice. However, if both characters are flawed, errors won't be corrected. FEC suffers the same problem with printed undetectable errors as ARQ mode.

PACTOR, like packet, uses a CRC block error detection system. Like AMTOR, errors can only be detected and then corrected by repeat transmissions. The CRC algorithm is quite robust and the chances of passing an incorrect block are very small.

HF Packet also uses a block CRC calculation to detect received errors which then must be fixed by repeat transmissions. As noted for PACTOR, the CRC algorithm is very robust. HF packet is, however, very susceptible to transmission errors. This generally results in a time-consuming process of sending repeats.

CLOVER is the only mode that includes error correction in its data encoding. The receiving station can correct a limited number of errors without requiring repeat transmissions. If the correctable error limit of the CLOVER mode is exceeded, repeat transmissions are used in ARQ mode. The Reed-Solomon algorithm is also very robust and the chances for undetected errors is very small.

Bandwidth and bandwidth efficiency

Signal bandwidth and its uses are very misunderstood parameters of a radio data signal. Often, the bandwidth of a mode is specified as that range of frequencies between the -3 dB or -6 dB points on a spectral plot of the signal. A more realistic measurement of bandwidth is to determine how closely in frequency two signals can be

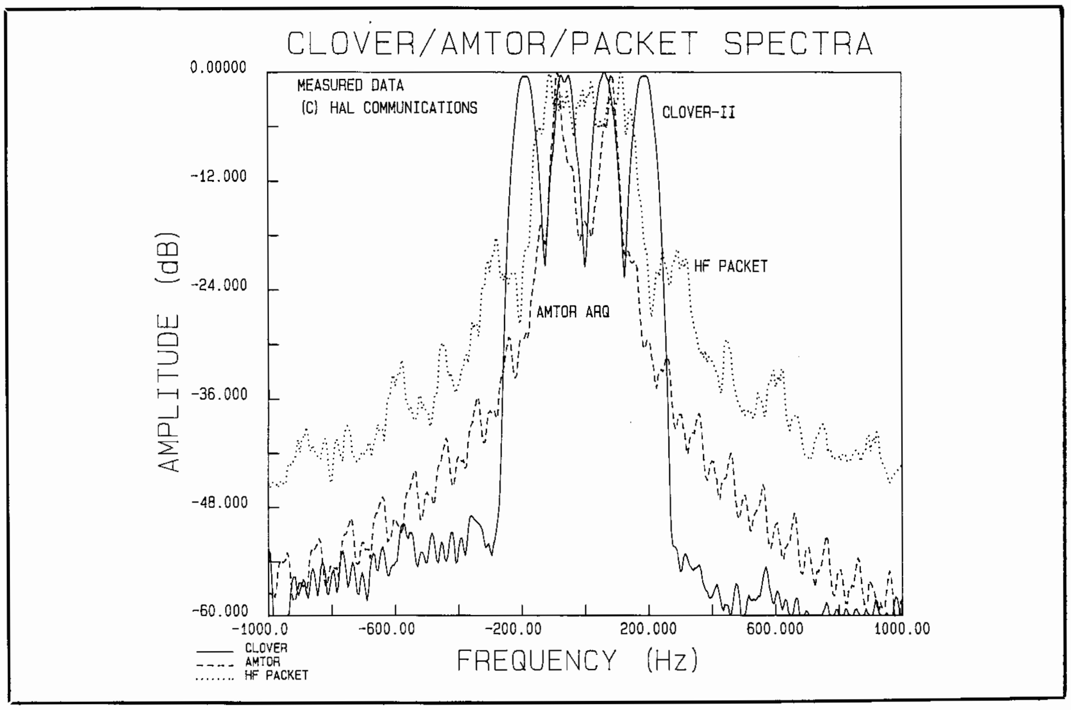

Figure 5. CLOVER/AMTOR/packet spectra.

placed without mutual interference. Because the signal strengths of two adjacent HF signals often vary by 30 to 50 dB, and all data modes (except CLOVER) have wide sidebands, minimum channel spacing is a much higher number than might be indicated by the −3 or −6 dB spectrum bandwidth.

Figure 1 shows the bandwidth of a CW transmitter sending code at 60 WPM. The −50 dB bandwidth of this signal is approximately 800 Hz (±400 Hz). You can't have two 60-WPM CW stations closer than 800 Hz to each other without potential mutual interference. This bandwidth scales with speed—a minimum spacing of 267 Hz

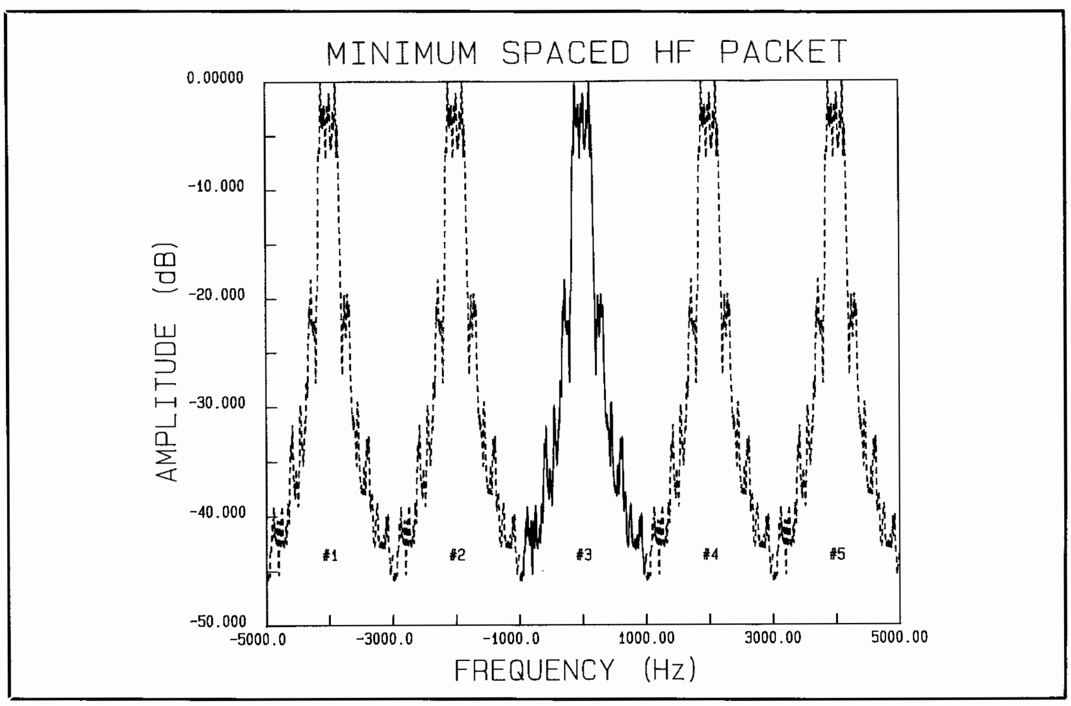

Figure 6. Minimum spaced HF packet.

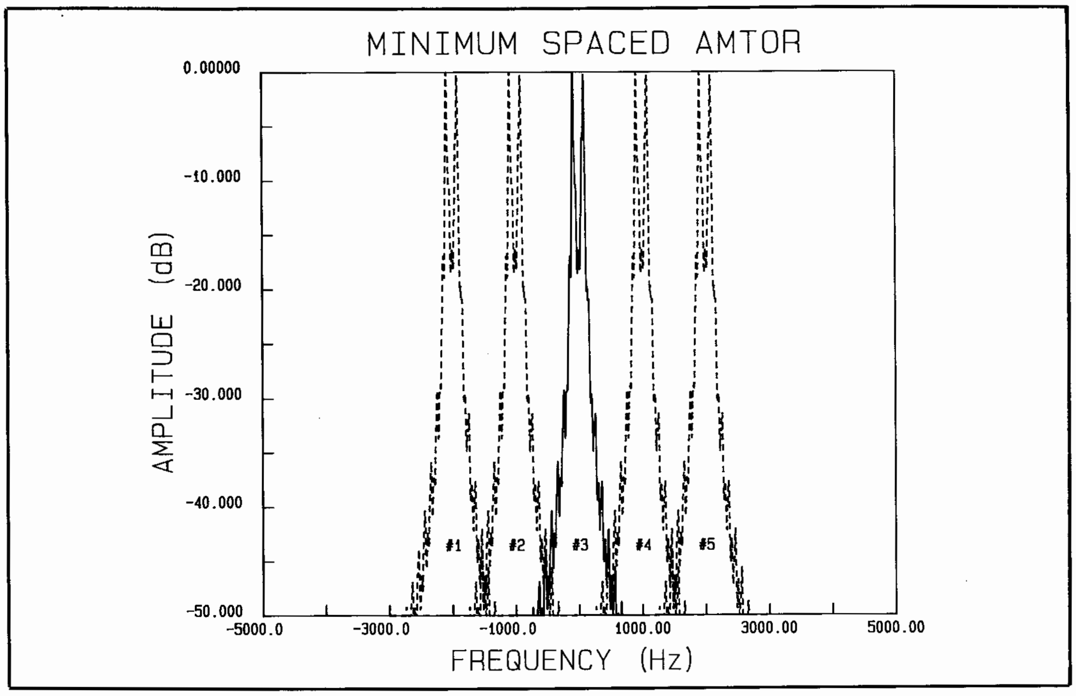

Figure 7. Minimum spaced AMTOR.

for 20-WPM signals. Here, the receiver selectivity becomes the controlling point. If all stations have a 500-Hz receiver filter, the minimum signal spacing is at least 500 Hz, regardless of CW speed. Note also that the "500 Hz" receiver filter bandwidth specification is almost always the −6 dB bandwidth, not the −50 dB bandwidth. Automatic CW reception is, therefore, probably limited to a minimum CW signal spacing of 1 kHz or more. The human brain is adaptive and interpretative, and we can indeed "copy through the QRM." A good CW operator can often decipher CW signals spaced as closely as 100 Hz, but only if the two signal strengths are similar.

Figure 2 shows the measured spectrum of an AMTOR signal. While this is a 170-Hz shift, 100-baud FSK signal, the curve can be taken as representative of all RTTY and AMTOR modes (45-baud RTTY will be slightly narrower, but not by much). Note that the −50 dB bandwidth of this curve is approximately 1200 Hz. Practical observation has shown that, if all stations use 500-Hz receiver filters, AMTOR stations can be spaced as closely as 1 kHz apart with little or no mutual interference. However, if either station in an ARQ link uses his 2.4-kHz SSB filter, the spacing must be increased to 1.5 or even 2.0 kHz. The same arguments apply to RTTY signals.

* The data plotted in **Figures 5, 6, 7,** and **8** are the same data shown in **Figures 2, 3,** and **4.**

Figure 3 shows the measured spectrum of an HF packet signal (300 baud, 200 Hz shift). Its −50 dB bandwidth is greater than 2 kHz! A minimum spacing of 2 kHz is, in fact, the practical limit based upon on-the-air experiences. Some HF packet stations use a 500-Hz receiver filter. This may help reduce interference in some cases, but the interference sidebands of an adjacent HF packet signal will still fall within the receiver filter's passband. Also, narrowing the receiver bandwidth to 500 Hz may introduce data distortion that compounds the already poor performance of packet radio on HF.

Figure 4 shows the measured bandwidth of a CLOVER-II signal. CLOVER-II signals are designed to eliminate sidebands. The −3, −6, and −50 dB bandwidths of CLOVER are the same—500 Hz. The CLOVER-II demodulator uses receiving filters that have passbands identical to the CLOVER-II spectrum. Therefore, CLOVER receivers are very resistant to interference from nearby signals—CW, RTTY, AMTOR, packet, even another CLOVER signal. CLOVER signals may be placed exactly "edge-to-edge" at 500 Hz spacing with no mutual interference; a "guard-band" is not required. Laboratory tests have shown that the co-channel interference rejection of CLOVER receivers is greater than 50 dB.

Figure 5* shows a combined plot of the spectrum of AMTOR, HF packet, and

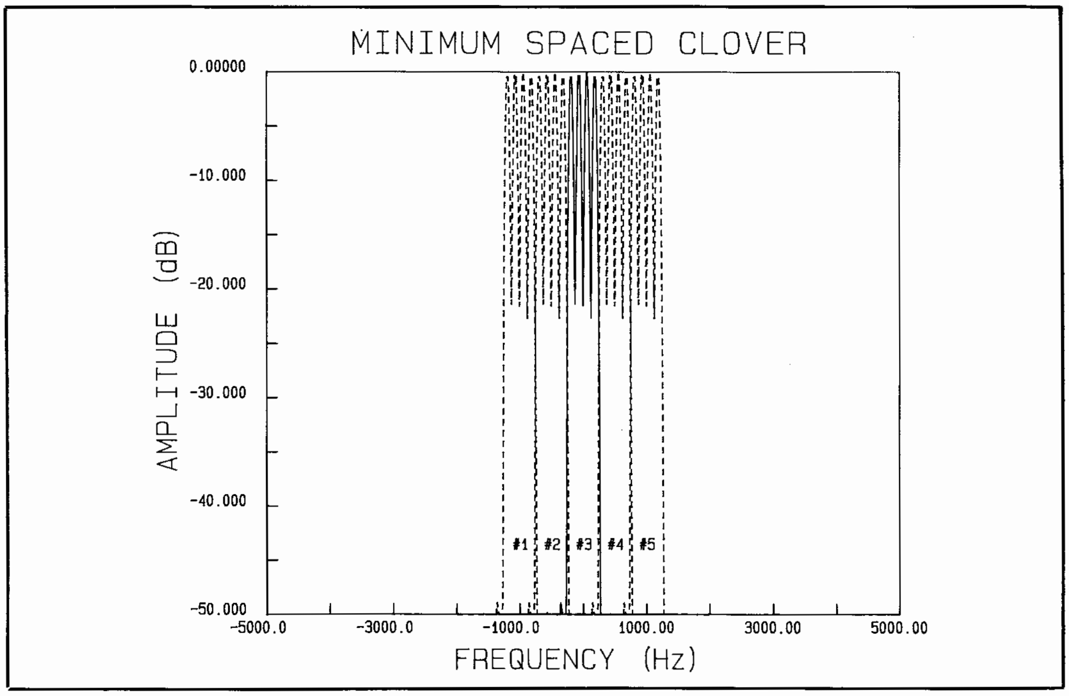

Figure 8. Minimum spaced CLOVER.

CLOVER signals. The wide sideband nature of AMTOR and HF packet is readily apparent, as is the very compact and concentrated spectrum of CLOVER.

Figures 6, 7, and **8** show how much bandwidth is required to support five minimally spaced HF Packet, AMTOR, and CLOVER signals, respectively (see the footnote for **Figure 5**). Five HF packet signals require 10 kHz of an HF band, five AMTOR signals require 5 kHz, and five CLOVER signals require 2.5 kHz of the band. Put another way, four CLOVER signals will fit in the same bandwidth required for one HF packet signal, and the data throughput is ten times higher on each CLOVER signal.

Summary

There are presently four different modulation and protocol formats used to send amateur data via HF radio: CW, RTTY, AMTOR, and packet. Two new modes have been developed that promise increases in the data speed: PACTOR and CLOVER. The six modes differ considerably in performance, each with its own advantages. CW requires minimum additional equipment to send and receive (key and good operator); RTTY equipment is relatively simple and easy to use. AMTOR offers error correction at modest data rates and is very robust for HF use. HF packet can send ASCII data at good speed when conditions are perfect, but quickly falls apart in typical HF conditions. PACTOR promises modest speed improvement and ASCII coding over AMTOR. CLOVER promises much higher data speeds, error correction, and efficient use of our radio spectrum. No one mode completely satisfies all aspects of the others.

Amateur radio experimentation with data modulation techniques is in the midst of a new explosion. This renewed interest comes as a result of the rapid growth of amateur data message systems by VHF packet radio and the emerging new DSP technology. The need and desire to send data more accurately and faster via HF radio would not exist without the growth of the packet radio traffic network. New modulation techniques like CLOVER would not be possible without DSP technology. Although we have concentrated only on the modulation and modem aspects of modern radio data transmission, it must also be recognized that the next "level"—inter-station communications protocol—is also undergoing rapid advancements that wouldn't have been possible without low-cost and readily available high-performance personal computers. It can truly be said that amateur radio is not "standing still." Amateur radio continues to lead the technology.

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More on CLOVER

The first CLOVER product available to amateurs will be a plug-in card for "IBM-compatible" PCs, manufactured by HAL Communications Corp. It will be called "PC-CLOVER," the "PCI-4000." PC-CLOVER was demonstrated first at the 1992 Dayton Hamvention® and targeted for delivery soon thereafter. Patents have been applied for CLOVER, CLOVER-I, and CLOVER-II technology by Ray Petit and HAL Communications. CLOVER, CLOVER-I, and CLOVER-II are registered trademarks. HAL plans to license CLOVER technology as freely and inexpensively as possible to all amateurs and amateur manufacturers.

PC-CLOVER will include a simple, single-operator application PC program to get you started. However, HAL would like to encourage all "network" software authors to write drivers to allow their programs to take advantage of the increased performance of CLOVER. The PCI-4000 hardware interface is specifically designed to work in network and "windowed" PC environments. An interface protocol definition document is being prepared for all who are interested.

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