CLOVER is a term you might have heard about in the past. If not, you certainly will be hearing about it in the future. K9GWT and W7GHM give us a rundown on this new form of HF data transmission.

CLOVER
Fast Data on HF Radio

BY BILL HENRY, K9GWT, AND RAY PETIT*, W7GHM**

If you operate RTTY, AMTOR, or packet, you've probably seen a few references on your screen to something called "CLOVER." "What is it and why do I need it?" is the usual reaction. Yes, "clover" (little letters) is a plant, sometimes "wished over" (and sung about by Arthur Godfrey). But "CLOVER" (big letters) is a new way to send data on HF radio that Ray Petit, W7GHM, has invented. This is the story of CLOVER, a project that continues to this date.

What is CLOVER?

CLOVER had its beginnings about 15 years ago when Ray and others were experimenting with very narrow bandwidth Morse code. It's called "Coherent CW."[1] When packet radio came along, Ray tried packet on VHF and then HF. As most of us have found, HF packet radio leaves a lot to be desired. The ionosphere is just not very kind to packet data, and often many repeats are required to pass any data at all on 20 meters. Unlike the rest of us, Ray quickly realized that putting "bandaids" on HF packet or AMTOR was just not going to do the trick; what was needed was a new approach. The new approach must be based on a thorough analysis of the real HF signal conditions and on techniques that can compensate for these conditions.

Ray started by just listening to real radio signals, observing their fades and phase changes on typical HF paths and under varying conditions; shortwave broadcast signals made great "test signals." Combining information from signal observations, reading, and previous work on Coherent CW, Ray devised a new way to send data on HF radio which he called "Cloverleaf." In July 1990 Ray published the first paper describing the mode in *QEX*.[2] The name "Cloverleaf" came from the observation of a scope pattern while watching the data; it was a perfect four-leaf clover. As Ray's work continued, the pretty scope pattern was lost to technology, but the shortened name "CLOVER" remains.

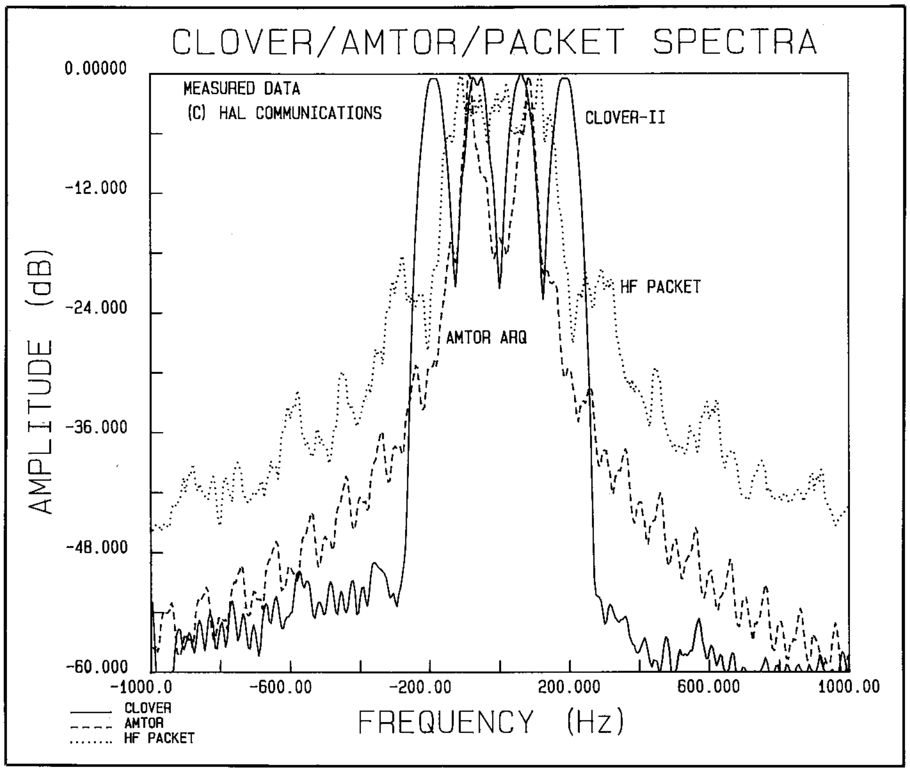

Fig. 1- Comparison of AMTOR, HF Packet, and CLOVER-II spectra.

Other amateurs had also been searching for a way to cure the problems we were having with sending data on HF. Bill Henry, K9GWT, and Jim Tolar, W8KOB, of HAL had also been working on the problem for several years. Ray's paper was like a breath of fresh air to us. *Finally* someone had taken the pains to start at ground zero and devise a modulation format that would work on HF. Very quickly Ray and HAL teamed up to continue work on his new "CLOVER Modulation."

Unique features of Cloverleaf include (1) multi-level phase modulation, not FSK; (2) use of sequential pulses whose state changed only between pulses (not when a carrier is on the air); (3) very low base data rates (25 bps); and (4) very tightly controlled frequency spectra with *no* sidebands (100 Hz total bandwidth to − 60 dB).

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Cloverleaf could pass error-corrected data over a typical HF path about two to three times faster than AMTOR or HF packet radio. Unfortunately, Cloverleaf also made extreme demands on the HF radio equipment. Radio frequency accuracy and stability had to be of the order of ± 0.1 Hz! This is way beyond the capabilities of any currently available commercial radio equipment. Ray also designed a complete transceiver to use Cloverleaf modulation.[3]

At the time when Ray and HAL first teamed up, Ray had already started work to include new DSP (Digital Signal Processing) technology in his Cloverleaf modem. DSP offered many advantages over the basically analog Cloverleaf circuitry, the major ones being (1) greatly reduced radio stability and accuracy requirements (to ± 10 Hz), and (2) faster data throughput (to 750 bps). Ray and I soon decided to put "all our eggs in the DSP basket." The original "Cloverleaf" modem was renamed "CLOVER-I" and the new DSP version dubbed "CLOVER-II."

Ray and HAL worked on development of CLOVER-II all through the fall of 1990 and spring of 1991.[4] The first working CLOVER-II modems were demonstrated at the Dayton Hamvention in April 1991. The new modem had a bandwidth of 500 Hz (to -60 dB), passed error-corrected data at rates up to 750 bps, and would work with "normal" HF transmitters and receivers. The Dayton demonstration equipment was admittedly "primitive" and there were many details yet to be worked out. However, Ray and I wanted to show it and see if there were any other amateurs who were interested. We were convinced that we had a marvelous machine, but the inventor can easily fall in love with his gadget, even if there is no market.

The results of the Dayton showing were beyond our wildest dreams. Everyone who saw CLOVER-II work was impressed—and wanted one or two!

As a result of comments from those at Dayton and from new ideas that developed as CLOVER-II was prepared for the show, we decided to build a new "universal" hardware base for development work, quickly dubbed "SUMMER CLOVER." HAL built a total of eight such units. Like Ray's original DSP design, SUMMER CLOVER units used Motorola DSP56001 and 68B09 processors. We had hoped that SUMMER CLOVER would meet all of our requirements and that we could build many of these units for use in "beta-testing" of the new mode.

Enter Murphy and his infamous law! First, SUMMER CLOVER hardware was extremely expensive—about $3000 each. We could not afford to build a lot of them to be loaned out for "beta-testing." Second, our "bright ideas" for features soon out-grew the capabilities of our hardware! Ray's software soon consumed the entire capacity of the 6809. DSP performance was also limited, since several "routine" processes had to be moved from the 6809 to the DSP56001.

In spite of these limitations, CLOVER-II in SUMMER CLOVER hardware worked very well. Ray devised an adaptive ARQ mode in which the modulation parameters are automatically adjusted to fit ionosphere conditions. We were able to put CLOVER on the air and run several tests. We also ran extensive laboratory tests under a number of different simulated conditions. Our avowed goal of increasing data speed to ten times faster than HF packet or AMTOR was easily met. As always happens in an R&D project, we also found a number of new areas to consider—and some features that needed improvement.

In November and December 1991 we went back to the drawing board. Ray and I both knew that we needed more microprocessor horsepower to do all that we wanted. We also realized that CLOVER would never be a success if each unit had to sell for $3000! What has evolved is still another hardware and software version which we call "PC-CLOVER." As the name implies, PC-CLOVER is a plug-in card for IBM-compatible personal computers. While we can't do much about the present high cost of DSP technology, PC-CLOVER does not need expensive cabinetry, power supply, and front-panel hardware, but does include the much needed additional processing power, primarily a 68000 IC instead of the 6809. These changes have reduced the price dramatically.

As this article is being written (early February 1992) PC-CLOVER development is well underway. A number of very thorny problems have already been licked. The first public exhibition of PC-CLOVER will be at the 1992 Dayton Hamvention.

How CLOVER Works

To adequately explain why we feel CLOVER is such a breakthrough, we must first briefly review the pluses and minuses of existing HF data modes—RTTY, AMTOR, and HF packet radio.

RTTY of course led the way for "automatic" reception of characters or data via HF radio. RTTY has been around since the 1940s and is very reliable. The techniques we use today to send and receive RTTY are much the same as those first used. We have better equipment, but use the same FSK modulation and Baudot or ASCII code. RTTY is slow and does not offer error correction. RTTY speeds of 60 WPM (45 baud) to 100 WPM (75 baud) are common. Increasing the RTTY speed increases the probability of errors; we generally use 45 baud.

AMTOR evolved from an existing ship-to-shore "radio telex" mode, often called "TOR" or "SITOR" (CCIR 476 and CCIR 625). AMTOR introduced us to a new type of data link—"ARQ mode" (ARQ stands for Automatic Repeat Request).

AMTOR characters are coded so that the receiving station can detect an error in each character sent. The sending station sends three characters, turns his transmitter OFF, and listens for a one-character response from the receiving station. The response is either "all OK, send next three," or "repeat last three characters." By this means AMTOR offers error correction. However, like RTTY, it is also "slow." Under the best of conditions AMTOR can pass data at an equivalent RTTY rate of 50 baud (6.67 characters per second). AMTOR is also limited to the same character set as Baudot—all capital letters and no ASCII control characters.

Because of the efforts of Vic Poor, W5SMM, and his APlink network program, AMTOR has seen a resurgence of interest over the past three years. AMTOR nets have also pioneered the use of frequency scanning radios to allow a bulletin board station (BBS) to serve many users at varying distances on different bands and frequencies.

HF packet radio is an out-growth of VHF packet radio, pioneered by the Tucson Amateur Packet Radio Corp. (TAPR). Like AMTOR, packet radio (AX.25) uses an ARQ-type of format to automatically sense errors and request repeats. However, packet radio supports the full 7-bit ASCII character set, including upper/lower-case letters and control codes. VHF packet radio works very well and has become the defacto VHF mode for data transmission.

Many aspects of packet radio, however, conspire to make its performance on HF very disappointing. The major problems with HF packet radio are (1) the modulation format (300 baud, 200 Hz shift FSK), (2) the AX.25 protocol (long blocks with only CRC error detection and large amount of overhead), and (3) the wide bandwidth required in today's crowded HF bands (2 kHz). Under perfect ionospheric conditions HF packet radio could send data at up to 20 ASCII characters-per-second. However, what happens in fact is that typical HF packet data is passed at only a rate of 4 to 6 characters-per-second (about the same speed as AMTOR), and a HF packet signal requires twice the bandwidth of an AMTOR signal.

Since all VHF traffic networks now use packet radio, HF packet radio networks have evolved to provide long-distance support. Pioneering work has been done by HF packet stations participating in the ARRL-sponsored "HF Packet STA" program. These fellows have invested a lot of time, money, and persistence in making HF packet work.

CLOVER intends to support the many advantages of AMTOR and HF packet radio *and* "fix" the major problems of these modes. The most serious limitation of RTTY, AMTOR, and HF packet is data throughput and how the data is used to modulate the radio signal. The ionosphere is not a "friendly" medium for data signals. HF signals often arrive at the receiving antenna by many different propagation paths; two or more paths are common. Each signal path has its own time delay, amplitude, and even different center frequency. The receiving antenna does not discriminate; it adds all signals and passes the composite on to the receiver. The amplitudes and phases of the separate AC signals combine algebraically to produce a widely varying receiver input. Deep selective fades and time-smearing of data pulse transitions are the usual result.

Once combined at the antenna, the individual path signals are not easily separated. It is usually impossible to compensate for all of these "multipath" effects in the demodulator. A good example of multipath ionosphere distortion is the "selective fading" we hear when listening to music from a shortwave radio station. While annoying when listening to music, this distortion can be totally destructive to data transmissions.

A major nonrecoverable parameter of HF data is the time at which the data state changes from MARK to SPACE, the data transition time. If we lose this information, the modem can no longer tell when one data pulse ends and the next begins or if the logic state should be a "1" or a "0." When two signals arrive with different propagation time delays, the composite antenna output signal is "smeared" and the transition times overlap. Measurements by Ray and many others show that we can expect this time overlap from different paths to be as much as 3 to 5 milliseconds (ms). Typical demodulators (and UARTs) must receive at least one half of each data pulse without distortion to determine the MARK or SPACE data state. Therefore, the narrowest data pulse which can be reliably demodulated is on the order of 6 to 10 ms, corresponding to maximum data rates in the range of 100 to 167 baud. Observation shows that the 100 baud limit is more realistic and even it can be too high for satisfactory data transmission at times.

HF packet radio uses a 300 baud data rate, a pulse width of 3.3 ms. Successful HF packet transmissions are therefore very unlikely if the signal is propagated by multiple paths. HF packet works well only when the operating frequency is close to the Maximum Usable Frequency (MUF)—when there is only one propagation path. Since this is the exception and not the rule, long-term packet performance on a single fixed frequency is pretty poor, and many repeats may be required to pass any data at all.

HF packet radio, AMTOR, and RTTY all use FSK modulation. One radio frequency is sent for the "1" or MARK pulse state and another for the "0" or SPACE state. The transmitter carrier frequency is shifted back and forth at the same rate as the data. CLOVER uses different modulation techniques. First, CLOVER shifts the *phase* and not the frequency of the carrier. Second, more than one bit of data can be sent per phase state. For example, BPSK (binary phase shift keying) has two phase states (0 or 180 degrees) which can be used to represent MARK and SPACE. QPSK (Quadrature PSK) has four phase states (0, 90, 180, and 270 degrees). A single phase change in QPSK represents the state of two binary bits of data. Similarly, 8PSK can send the state of 3 bits per phase change and 16PSK can send 4 bit states per phase change.

CLOVER also allows use of Amplitude Shift Keying (ASK) in the 8PSK and 16PSK modes. We call these modes "8P2A" (4 data bits per phase/amplitude change) and "16P4A" (6 bits per phase/amplitude change). Since all changes in phase or amplitude occur at the fixed base rate of 31.25 bps (an equivalent pulse width of 32 ms), data errors due to multipath time smearing of data transitions are minimized.

The CLOVER modulation "strategy" is to always send data at a very slow base modulation rate and to use multi-level changes in phase or amplitude to speed-up data flow. One final twist to CLOVER-II is that there are *four* separate transmitted pulses, each separated by 125 Hz. Each of the four pulses may be modulated by BPSK through 16PSK plus 8P2A or 16P4A modulation. This further multiplies the effective data throughput by a factor of four. Putting it all together, CLOVER can send data at rates from its base data rate (31.25 bps) to 24 times its base data rate (750 bps). Wow! It's almost like something for nothing! Not so by a long shot. There are still problems to be solved!

PSK modulation itself poses some pretty serious problems. If we modulate a *continuous* carrier using PSK, the frequency spectrum we get is *very* bad for HF use, as sidebands are strong and extend over a wide spectra. CLOVER avoids this problem by two techniques: (1) each of the four tones is an ON/OFF amplitude pulse and the phase is changed only when the pulse is OFF; (2) the amplitude waveform of each ON/OFF pulse is carefully shaped to minimize the resulting frequency spectra. Combined, these techniques produce a composite CLOVER spectra that is only 500 Hz wide down to −60 dB. This is one half the radio bandwidth required for AMTOR and one quarter that for HF packet radio. A comparison of AMTOR, HF packet, and CLOVER spectra is shown in fig. 1.

Detecting PSK is a lot more difficult than detecting FSK. We need a very accurate phase reference to determine which phase state is being received. Analog phase detection and PSK recovery circuits can be *very* complicated and expensive. Fortunately, the microprocessor and now DSP have greatly simplified the task.

DSP is the key to making CLOVER modulation practical. Phase reference determination, phase detection, and pulse amplitude shaping are all tasks performed very rapidly by the DSP. However, CLOVER modulation is sensitive to phase inaccuracy (or "dispersion"). To sense 16PSK levels, we must be able to detect phase changes of ±22.5 degrees and be synchronized to the transmitted signal to within ±12.25 degrees. Since the ionosphere adds phase "dispersion," a good stable signal—and lots of DSP processing—is required to make this measurement. As CLOVER progresses from BPSK to 16PSK to increase data throughput, increasingly better signals are required. However, when signals *are* good, CLOVER takes full advantage and really "moves the bits."

CLOVER also takes a different approach to error correction. AMTOR and packet radio both correct errors by sensing errors at the receiver and then requesting repeat transmissions. When there are errors to be fixed, data throughput is slowed by the time it takes to send the repeats. When conditions are poor, packet radio often bogs down, sending only repeats and no data; AMTOR will slow-down considerably under the same conditions.

CLOVER uses a Reed-Solomon error-correction code[5] which allows the receiver to actually fix a limited number of errors *without* requiring repeat transmissions. For a moderate number of errors, CLOVER does not require repeats and data continues flowing at the no-error rate. To distinguish between the two schemes, we classify AMTOR and packet radio as "error-detection" protocols and CLOVER as an "error-correction" protocol. In addition, like packet radio, CLOVER includes a CRC (Cyclic Redundancy Check sum) which is used when conditions are very bad and the number of errors exceeds the capacity of the Reed-Solomon error corrector.

CLOVER ARQ mode is also adaptive. As a result of the DSP calculations necessary to detect multi-level PSK and ASK, the CLOVER receiver already has information which can be used to determine the signal-to-noise ratio (S/N), phase dispersion, and time dispersion of the received signal. CLOVER has 8 different modulation modes, 4 different error correction settings, and 4 different data block lengths which can be used—a total of 128 different modulation/code/block combinations.

Using real-time signal analysis, the CLOVER receiver will automatically signal the transmitting station to change modes to match existing ionosphere conditions. When propagation is very good, CLOVER can set itself to the highest speed and data literally "screams" down the path. When conditions are not so great, the data speed is slowed. As noted earlier, the CLOVER character throughput rate under typical HF conditions is about ten times faster than AMTOR or HF packet. However, when we get one of those "perfect ionosphere" conditions, CLOVER will "shift gears" and pass data at 50 to 100 times the speed of AMTOR or HF packet radio. In all cases, CLOVER automatically changes speeds to give the maximum speed that the ionosphere will allow.

Is CLOVER Legal For Amateur Use?

We hear this question often. The short answer is yes. The reason lies in the definition of the CCIR Emission Designator[6] and how that matches our FCC Part 97 Rules and Regulations. As can be seen in fig. 1, CLOVER bandwidth is 500 Hz—no doubt about it! Since the CLOVER modulator generates tones which drive an LSB transmitter, the modulation mode is "J2." One possible point of confusion: While CLOVER does use multiple tones and multiple modulation levels, CLOVER is *not* a multiplex emission; we are sending only one data stream over the air. The full CCIR emission designator for CLOVER is "500HJ2DEN." This all agrees with FCC Part 97 Rules and Regulations.

Summary

This is the "promise" of CLOVER. The mode has evolved from the need to pass data via HF radio at a faster rate and from an observation of the real-world propagation conditions. It answers a pressing need to send data more reliably and faster than can be done using AMTOR or HF packet radio. CLOVER is admittedly a very complicated mode that has only recently become practical due to the advent of relatively low-cost DSP devices. CLOVER is also very bandwidth efficient, requiring a small fraction of the spectra of AMTOR (one half) or HF packet radio (one quarter).

Although bandwidth efficiency may not at present be high on the amateur's list of "must haves," we must realize that while amateur radio itself is growing, our HF frequency allocations are likely to remain fixed. In the future, we must find ways to cram more signals into our available HF spectrum. Like SSB versus AM, CLOVER's bandwidth reduction allows us to make more efficient use of the limited HF bands we have. CLOVER is still evolving as this article is being written.

Footnotes

1. For more information about Coherent CW, see "Coherent CW—Amateur Radio's New State of the Art?", Ray Petit, W7GHM, *QST*, September 1975, pp. 26-27. "Coherent CW—The CW of the Future," Adrian Weiss, K8EEG/Ø, *CQ*, June 1977, pp. 24-30; July 1977, pp. 48-54. "Coherent CW," Charles Woodson, W6NEY, *QST*, May 1981, pp. 11-14; June 1981, pp. 18-23.

2. "The CLOVERLEAF Performance-Oriented HF Data Communication System," Ray Petit, W7GHM, *QEX*, July 1990, pp. 9-12; reprinted in *ARRL/CRRL 9th Computer Networking Conference Proceedings (1990)*, pp. 191-194.

3. "Frequency-Stable Narrowband Transceiver for 10100.5 kHz," Ray Petit, W7GHM, *ARRL/CRRL 9th Computer Networking Conference Proceedings (1990)*, pp. 191-194.

4. "CLOVER-II: A Technical Overview," Ray Petit, W7GHM, *ARRL Amateur Radio 10th Computer Networking Conference Proceedings (1991)*, pp. 125-129.

5. Reed-Solomon encoding modifies transmitted data in a pattern that the receive modem uses to detect and correct errors caused by ionospheric distortion. Transmitting and receiving CLOVER modems are synchronized so that original bit patterns are restored when receive data is processed and passed to the data terminal. This type of "Forward Error Correction" (FEC) allows correction of errors without requiring repeat transmissions.

6. For more information about CCIR Emission Designators, see *The ARRL Handbook* (recent edition), Chapter 9, "Modulation and Demodulation."

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