A STUDY OF HIGH SPEED PACKET RADIO

Roy E. Gould. N5RG
4752 DeBeers Drive
El Pass, TX 79924

ABSTRACT

Some of the possible transmission methods that could be used in the high speed packet radio network are discussed and analyzed. The conclusion is reached that a good approach is to directly FSK the RF carrier at 38.4 Kbaud. A 100 kHz RF bandwidth channel above 228 MHz should be used and a scrambler should not be used. The radio should be designed using modern IC's so that a simple and relatively inexpensive yet high performance radio results,

INTRODUCTION

A major advancement that must be made if packet radio is to reach it5 potential is the development and operation of a high speed network operating on the vhf and uhf bands that enables very fast and highly reliable digital information transfer in the local area as well a5 between widely separated points. Ideally, this network should be fast enough that transferring information between packet bulletin board systems or between TCP/IP stations will not adversely slow down QSO's between individual operators. As pointed out by Bdale Garbee in his paper 'MORE AND FASTER BITS" (Ref 1) it should be so fast that such things a5 digitized voice and computer graphics became practical, Most likely, the applications that become practical because of the high speed and high throughput of the network will grow to the paint that even the highest channel capacity will be fully utilized, at least part of the time, While there will most likely always be a place for law speed packet, there seems little point in the fang run in having a local area network running at a different speed than the " backbone" . They should both run at the same high speed,

Packet radio is still in its infancy and the decisions we make today regarding transmission standards will have a far reaching influence that will be difficult to erase. Once a network is built using a particular standard it will be very difficult to change even if some new method offers greatly increased performance. Therefore, it is important to take the time to figure out what the best approach is and to get started on the right foot. It will be more efficient to go directly to the ultimate standard rather than taking several intermediate steps requiring rebuilding the network several times, It is important to design the network from the beginning to have a5 high a transmission speed a5 practical while at the same time taking into account the difficulty and cost of building the network and with the view in mind that it will eventually replace the current 1200 baud system. I hope that this paper will give you some ideas and that it will help to formulate a common standard that all Amateurs can work from and to which manufacturers can build equipment so that the next step in building the packet network can take place.

HOW PACKET IS TRANSMITTED

Understanding the way in which packet radio signals are transmitted is essential for understanding what is needed in a packet radio link. Three important attributes of a packet signal are 1) the bits are sent synchronously, 2) Non Return to Zero Inverted (NRZI) encoding is used, and 3) bit stuffing is used.

Packet radio bit streams are transmitted synchronously. There are no start and stop bits associated with each byte of information a 5 is done on RTTY or on the FE-232 communications line between your TNC and computer. If threceiver does not lose lock then start or stop bits a r e not necessary to maintain synchronization with the bit stream. A series of flags at the beginning of the transmission is used to establish the initial byte synchronization.

The packet bit stream is sent using Non Return to Zero Inverted encoding. A logic one is sent by not changing state and a logic zero is sent by changing state. This means that when a series of ones is sent there is no change in the signal. When a series of zero's is sent, the state changes for each zero. One important implication of NRZI encoding is that mark and space lose their significance. It is only the change in state that is important. No change means "1" and a change means "0". The receiving equipment must remember what the last state was so that it can compare the last state with the current state so that it can determine whether the current state is a one or a zero.

Bit stuffing is used to insure that the flag will be unique and to make sure that the signal cannot stay in one state for an extended time so that the receiver will see a transition in state often enough to maintain lock on the bit stream. Except when sending flags, if five logic ones occur in sequence, the transmitter "stuffs" in a logic zero before the next bit is transmitted. The use of zero stuffing insures that inside the packet bit stream the longest string of logic ones that can occur is five, The flag is 7E Hex. Therefore, sending the flag require5 the transmission of six logic ones in a row. The use of the combination of NRZI and bit stuff ing insures that the signal will not stay in the same state for very long so that a data clock ran be readily derived from the signal. This also, i n effect, scrambles the signaIt i s not clear to me that any further scrambling of a packet signal a5 is done in the G3RUH and the Heatherington modems actually doe5 anything benif icial.

The highest frequency that must be transmitted occurs when a string of NRZI zeros is transmitted. In this case the state changes at each bit. This means that the highest keying frequency is one half the baud. For example, for a signal at 4800 baud, the highest frequency that must be transmitted is 2400 Hz if the harmonics of the square wave keying signal are filtered off. That the baud is double the highest frequency transmitted is consistent with the Nyquist-Shannon theorem. (page 129 of Ref 2)

SPECTRAL EFFICIENCY

It is helpful to have a method for comparing the relative efficiency of various transmission methods so that a judgement can be made as to which method makes the best use of the spectrum. One way to do this is to compare the Spectral Efficiency (bits per second being transmitted per Hz of bandwidth required for the transmission. i.e (bits/sec)/Hz) of the methods being considered (see pages 304 & 394 of Ref 3). There are two types of bandwidth that could be used: 1) baseband or 2) RF bandwidth. Baseband is the bandwidth of the system from the input to the transmitter to the detected signal output, while the RF bandwidth is the bandwidth of the RF signal itself. It is important to define which type of bandwidth is being used in a particular calculation of spectral efficiency,

One of the more efficient methods used on commercial sate1 1 ite channels achieve5 4.5 bits/s per Hz of baseband bandwidth in practice (see TABLE 2.15 of Ref 4). An interesting question to ask is "how good is the common packet radiu transmission using the Bell 202 modem standard that everyone uses for 1200 baud transmissions on 2-meters ?" A look at Fig 2a in the paper "9600 Baud Packet Radio Modem Design' found in Ref 1 indicates that the baseband bandwidth of a NBFM radio link could be conservatively called 5 kHz. Using this number the spectral efficiency of the 2-m transmission is computed to be 0 2 4 bits/sec per Hz. The commercial satellite channel with it5 throughput of 4.5 bits/s per Hz passes information 18 times faster for a given bandwidth than we do on our 2-meter packet radiu channel ! There is a lot of room for improvement here!

MULTI-BIT TRANSMISSION

Amateurs are accustomed to thinking of sending digital information one bit at a time. That is the way Morse code and the teletype machine works. Packet radiu as currently used sends me bit at a time and so dses your computer to TNC link when it communicates over the RS-232 cable. But that is not the only way that things can be done. In the commercial satellite world, one bit at a time is usually not done and is in fact not allowed by the FCC rules for high capacity channel5 because it is too wasteful of spectrum, (see page 103 of Ref 4) It is also a matter of economics. The communication satelli te ha5 a limited amount of spectrum available and using it efficiently makes more money for the satel1 i te operator.

A method that is often used to convert an existing analog link to a digital link is to use a scheme such a5 this: The signal is transmitted using four different fixed carrier shifts. The signal is detected using the same discriminator that would normally be used for ordinary FM detection. A set of comparators followed by logic is used to determine which of the four frequencies is being transmitted, Since it takes four different states to define the state of two bits, each of these frequencies defines a unique state of the two bits, Each signaling interval transmitted is equivalent to transmitting two bits, yielding a theoretical increase in transmission speed of two.

Even though there are techniques far sending more than one bit at a time, they are probably more complex than can be justified at the present state of development of Amateur digital communication art. It seems relatively easy to increase the efficiency of Amateur packet transmissions to 1.0 or to even 2.0 bits/s per Hz of baseband bandwidth without resorting to multiple bit transmission. This is an improvement of 4 to 8 over current pract i ce on 2-m. The addi tional compl icat ions and expense of reaching transmission efficiencies greater than 2 bits/s per Hz de not seem justified at stage of development, However, it should nut be forgotten that it is possible to increase the spectral efficiency by transmitting multiple bits per signaling interval if the need should arise in the future for more efficient use of the spectrum.

SURVEY OF MODULATION METHODS

According to Ref 3, page 166, there are three attribute5 of a signal that can be modulated -- its amplitude, frequency, and its phase, With the exception of Morse code which is AM, Radio Amateurs have traditionally used some form of FM for digital communications. There are currently two different ways of modulating the information onto the RF carrier being used in the packet radio world, One of these is to frequency shift key (FSK) the RF carrier directly with the packet bit stream, The other is to audio frequency shift key (AFSK) an audio carrier with the packet bit stream and then to FM the RF carrier with this modulated audio carrier.

FSK of the RF Carrier

The typical 300 baud transmission on 20-meters in effect modulates the packet bit stream directly onto the RF carrier using FSK. This is usually done by translating a 200-I-k shift AFSK signal to RF by mixing in a ssb transmitter-, Even though the signal is coming from a ssb transmitter, the transmi tted signal is a FSK signal with a shift of 200 Hz that could be detected directly by an FM receiver instead of the normally used ssb receiver. If the signal was detected by an FM receiver , the packet bit stream could be taken directly from the FM detector. The theoretical spectrum generated by this signal shown in TABLE-1 indicates that the RF bandwidth required by this signal is a little mare than twice the baud. Bandwidth is based upon the definition of bandwidth given in the FCC rules which says that bandwidth is "The width of a frequency band outside of which the mean power of the total emission, is attenuated at least 26 dB below the mean power of the total emission, including al lowances for transmitter drift or Doppler shift." (97.2a8, Ref 5) The ampl i tude shown in TABLE-1 is the power level of the sideband below the total power in the emission.

FM by a FSK Audio Tone

Even though the 1200 baud signal used on Z-meters begins in a similar way to that on 20-m, the transmitted RF signal is quite different= The packet bit stream first frequency shift key5 an audio carrier between the 1200 and 2200 Hz Bell 202 standard tones. Then this audio signal drives the FM modulator of an FM transmitter i.e. the FSK modulated audio carrier is FM'ed unto the RF carrier, When received by an FM receiver, the modulated audio carrier (not the bit stream itself) is recovered by the discriminator and must be detected one more time by the FSK demodulator in the TNC to recover the packet bit stream,

The main advantage of this method is that it allows an ordinary NBFM voice radio to be used fur packet radio. Unfortunately, a5 the theoret ical spectrum for this signal presented in TABLE-2 shows, it does nut make good use of the RF spectrum, Applying the -26 dB FCC bandwidth rule indicate5 that about 9600 Hz of RF bandwidth is needed to transmit at 1200 bits/s fur a bandwidth efficiency of 0.125 bits/s per Hz of RF bandwidth This is a conservative estimate because many stations are deviating more than 2200 Hz.

The ampl i tude of the sidebands shown in SABLE-2 have been reduced 3 dB because i t has been assumed that an equal number of 1200 and 2400 Hz bursts are being sent, Amplitude a5 used in TABLE-2 is the average power of the sideband below the total power in the emission.

TABLE-1

Theoretical RF Specturm of a 300 baud, 200 Hz shift FSK Signal Transmitting NRZI zeros.

Sideband Pair	Amplitude (dB)
carrier	-1.6
+/- 150 Hz	-8.1
+/- 300 Hz	-21.4
+I- 450 Hz	-30.2

no keying filter used,
deviation = (4/pi) * 100 Hz

TABLE-2

Theoretical RF Spectrum of a 1200 baud Signal Sending Bell 202 Tones Deviating 2.2 kHz

Sideband Pair	Amplitude (dB)
carrier	-12.1
+/- 1200 Hz	-7.7
+/- 2200 Hz	-10.1
+I- 2400 Hz	-13.0
+/- 3600 Hz	-22.6
+/- 4400 Hz	-21.7
+/- 4300 Hz	-35.1
+/- 6000 Hz	-4% 5
+/- 6600 Hz	-37.1

The 300 baud ssb method used on 20-m makes good use of the spectrum and has an efficiency of nearly 0.5 bits/s per Hz of RF bandwidth, Contrast this with the 1200 baud Bell 202 modem method used on 2-m which has an efficiency of only about 0.125 bits/s per Hz of RF bandwidth If we used the 20-m type of transmission on vhf or uhf we would realize a substantial improvemen t in RF bandwidth utilization,

The Heatherington RF Modem

The transmission methods dicussed so far have employed FSK of either the RF carrier or an audio carrier by the packet bit stream. But there are other ways to transmit the packet signal. h e of these is used in the RF Modem designed by Dale Heatherington (WA4DSY) which is described beginning on page 68 of Ref-6. It can run bauds ranging from 9600 to 56,000. It is called an "RF modem" because its radio input and output is at 29 MHz and its data input and output is the packet bit stream, A linear transverter must be used with it to generate RF output on the band of interest, Good use is made of the spectrum since an RF bandwidth of 70 kHz is required to transmit 56 kbits/s. This is a RF bandwidth spectral efficiency of 0.8 bits/s per Hz.

The modulation used is a bandwidth limited form of Minimum Shift Keying (MSK). (see page 195, Ref 2 for a description o f MSK) The carr ier phase is shifted plus or minus 90 degrees for each bit, The modulator synthesizes the signal from quadrature component5 a n d is therefore very versatile i n the waveforms it can produce, A scrambler is used to improve clocking and to make the modulated signal appear to be noise. It appears to b e a versati le system that can operate at the highest legal baud. The main disadvantage is that it is relatively expensive because it requires both the RF modem and a linear transverter to make up a complete system.

A question that might be asked is "how well could we do if we directly FSK the RF carrier with the 56 Kbaud packet bit stream?". In an attempt to answer this question, the restraint is imposed that a linear FM modulator is used and that the packet bit stream passes through a low pass keying filter with a gain of -2 dB at 28 kHz. The keying filter removes the harmonics of the square wave keying signal and reduces the amplitude of the fundamental of this keying signal to 1. This helps to reduce the amplitude of the sidebands above the second sideband to an acceptable level.

The theoretical spectrum of such a signal for three different shifts is shown in TABLE-3. It appear5 that the optimum shift is about 28 kHz. At this shift the 100 kHz bandwidth l imitation imposed by the FCC rules for packet signals above 220 MHz can be met while at the same time utilizing as wide as possible shift for the best signal to noise ratio.

TABLE-3

Theoretical RF Spectrum of a 56 Kbaud FSK Signal
Transmitting NRZI Zeros CLP Keying Filter Used)

Sideband Pair	Amplitude (dB) for shift of 14 kHz	28 kHz	56 kHz
cam-ier	-0. 1	-0.5	-2.3
+/- 28 kHz	-18.1	-12.3	-7.1
+/- 56 kHz	-42.1	-30.2	-18.7
+/- 84 kHz	-69.7	-51.8	-34.1

I t appears to me that unless the Heatherington system achieve5 a significant improvement i n reception under weak signal conditions that it5 complexity and high cost cannot be justified when compared to a system using direct FSK of the RF carrier.

Amplitude Modulation

From a technical point of view, amplitude modulation could be used in a packet radio fink and dues have some advantages- Nate that the FCC rules do nut permit AH in a telegraphy l ink designed far automatic reception of the signal. Consider far a moment the problem of achieving 19.2 Kbaud on 2 meters where the FCC rules limit the bandwidth to 20 kHz. One way to do this is to use AM. A low pa55 filter with 2 dB attenuation at 9600 Hz is required to attenuate the high frequency components from the keying signal and to prevent overmodulation. In the worst case condition of sending a string of NRZI zeros, the RF signal would be 100 percent modulated with a 9600 Hz sine wave. The spectrum for this signal ha5 only three components - the carrier and two sidebands, The carrier amplitude is -1.8 dB below the mean power of the total emission and the two sidebands which are spaced at +/- 9600 Hz from the carrier are down -7.8 dB. The bandwidth of the signal is 19.2 kHz so the bandwidth requirement has been met.

A radio l i n k using AM should work well, especially when used in a VHF or UHF radio link. AM has proven effective for many years for the transmission of Morse code on the low bands, And the fact that it can be received by machine5 has been demonstrated by the many amateurs who have used various types of equipment currently available ta copy Morse off the air and display the text on the computer screen. AM has the disadvantage that it is somewhat more difficult to produce a 100 percent modulated signal as compared to FM. It ha5 the advantage that it can be easily detected at higher IF frequencies such as 10.7 MHz whereas NBFM cannot . Use af AM would reduce heating of the final amplifier. An AM packet radio system could be made to work and would probably work well.

Spread Spectrum

A relatively new method of transmission allowed by the FCC rule5 is spread spectrum (SS). The rules explain that SS may be used only abave 420 MHz, Only frequency hopping and direct sequence transmission5 are authorized. See 12.3, Ref 3 fur a description of SS. A fundamental characteristic of SS is that the transmitter's power is spread over a wide bandwidth and most conventional receiver5 will nut even notice that the SS signal. is present. It can provide low error rate5 and many statians can use the same channel simultaneously without interfering with each other. Sounds like just what we need for packet.

Sections 5. 11.2 through 5.11.6 of Reference 2 discusses many aspects o' using SS in various sorts of multiple access radia links including even a CB radio scheme. Some af the advantages listed are (a) immunity to QRM. (b) security of information in ttie channel , (c) immediate random access to the channel by a number af users and (d) graceful deqradatian of the channel with overload. SS might be the ideal way to go in a shared channel packet radio situation, however, this subject requires a considerable amount af research beyond that dune for this paper to determine if it is actually practical.

CONCLUSIONS

Operat ing packet at 1200 baud using Bell 202 tunes through NBFM radios should be abandoned for all serious packet work. It should be replaced with radio fink5 running 38.4 Kbaud or higher. Packet operation must be shifted ta frequencies above 220 MHz became the FCC rules da not allow the higher baud5 below that frequency3 Direct FSK of the RF carrier by the packet bit stream should be used. The deviation in hertz should be the same a5 the sending speed in baud (modulation index of 1). The transmitter should use a linear true FM modulator. A law pass keying filter should be used far bandwidth control. A modem is nut required since a logic level keys the transmitter and a logic level came5 out of the receiver. The use af a scrambler is not recommended unless it can be shown that it actually improves packet radio transmission quality or reduces the bandwidth required,

Operation at 38.4 Kbaud is recommended because the amplitude af the second sidebands of an FSK signal sending NRZI zeros with a modulation index of 1 exceeds -26 dB dawn, If 38.4 Kbaud is used these second sidebands wiIl be spared at +/- 38.4 kHz from the carrier and will be comfortably within the 100 kHz bandwidth allowed by the FCC rules. The maximum legal baud af 56 Kbaud is only 1.46 times higher than 38.4 Kbaud so this is a reasonable trade-off.

Because a 38.4 Kbaud packet signal is a wideband signal the receiver can be simpler than a NBFM receiver. It is not necessary to convert dawn to a low frequency IF such a5 455 kHz to obtain good FM detection a5 is usually done for NBFM. A single conversion receiver to 10.7 MHz will work f ine. Frequency stability does not have to be as quad fur the wideband signal a5 far NBFM.

One possibility for a receiver is ta convert a standard FM broadcast receiver. The IF bandwidth of such a receiver is about 250 kHz which is wider than the ideal bandwidth of somewhat mare than 100 kHz. The front end, mixer, and LO would have to be converted to work at the frequency of interest. A connection would have to be made to an appropriate DC coupled output from the FM detector. The output from the detector would drive a comparator to produce a logic output. While a broadcast receiver might be made to work, this probably is not the best solution.But advantage should be taken of the mass produced and inexpensive components such as ceramic IF filters and detector coils for 10.7 MHz that are manufactured far these receivers.

There are at least twa single chip receiver IC's available that appear to be ideal far application in packet radio receivers: the Motorola MC3356 and the Signetics NE605N. The MC3356 is a FSK receiver designed to operate up to 500 Kbaud. The IC contains 3 complete receiver with mixer, oscillator, IF, FM detector, squel ch, S-meter output, and data comparator. Unfortunately, its maximum rated operating frequency is only 150 MHz. Chances are that at least some units will wark satifactorily at 228 MHz, The addition of a GaAs Fet preamp in front of the IC should w-abuse a high performance receiver. The MC3356 costs less than $4 in quantities of one.

Another very promising single chip FM receiver chip is the NE605N. Its mixer operates up to 1000 MHz and its on board LO is good up to 500 MHz! It contains an IF amplifier, limiter, FM detector, S-meter output, and a squelch switch. An external analog comparator is needed to convert the quadrature detector output to a logic level. The NE605N costs less than $6 for one.

Another possibility is ta convert a NBFM receiver to wide band operation by connecting the IF amplifier and following circui try from the MC3356 to the output from the first mixer. The receiver would then function in both wide band and narrow band FM made5 simultaneously.

The transmitter can be of mare or less canventianaf design except that the oscillator must be capable of wideband true FM, A suitable oscillator is described in Ref 7. Advantage should be taken of this oscillator's capability ta operate at the 5th crystal overtone ta reduce the number af multiplier stages required. The oscillator would drive a multiplier chain and power amplifier. An oscillator of this type could be substituted for the oscillator in a NBFM tranmsitter to convert it to wideband packet aperation.

Unfortunately, wideband radius sui table for 38.4 Kbaud do nut currently exist so a suitable design must be developed. Fortunately, these new radios can be designed fur 220 MHz and abuve almost a5 easily a5 far 144 MHz. It appears that a wideband packet radio transceiver is simpler than a NBFM radio and can be bui it simply and inexpensively. By taking advantage of modern IC's and circuit modules, such a radio could be of simple enough design that it could be built by many Amateurs in a few hours. Once it is clear that there is a demand for such a radio, manufacturer5 will begin to build store bought radios and a new era in packet radio will begin.

REFERENCES

1: 7th COMPUTER NETWORKING CONFERENCE, The American Radio Relay League, 1988
2: REVIEW OF DIGITAL COMMUNICATIONS, J. Das, John Wiley & Sons, 1988
3: Digital Cellular Radio, George Calhoun, ARTECH HOUSE, 1988
4: RADIO SYSTEM DESIGN FOR TELECOMMUNICATIONS, Freeman, John Wiley & Sons, 1987
5: Reorganization and Deregulation of Part 97, Rules Governing the Amateur Radia Service, FCC, Federal Register, Vol. 54, No. 117, June 20, 1989
6: 6th COMPUTER NETWORKING CONFERENCE, The American Radio Relay League, 1987
7: Design method yields low-noise, wide-range crystal osci l lators, Tim L. Hillstrom, EDN, March 17, 1988, page 141