9600 Baud Packet Radio Modem Design

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ABSTRACT

The theoretical minimum audio bandwidth required to send 9600 baud binary data is 4800 Hz. Since a typical NBFM radio ha6 an unfiltered response from zero some 8 kHz, transmission of 9600 baud binary data i6 perfectly possible though it. This paper describe6 a successful implementation.

INTRODUCTION

The standard packet VHF/UHF radio data rate is 1200 baud because all TNCs provide an internal modem for this speed, and the two-tone AFSK audio spectrum suit6 unmodified voiceband radios comfortably. However, all TNCs can generate much higher data rates, and most FM radios have an unrealised audio bandwidth of some 7-8 kHz or more. So in many cases 9600 baud radio transmission is entirely practical with them.

This design is a high performance full duplex modem designed for packet use with most voiceband NBFM radios, assuming only minor modifications.

A key feature of this modem is it6 digital generation of the transmit audio waveform. Precise shaping compensates exactly for the amplitude and phase response of the receiver. This results in a "matched filter" system, which means that the received audio offered to the data detector has the optimum characteristic ("eye") for minimum errors. It also allows very tight control of the transmit audio bandwidth.

MODEM FEATURES

Here is a summary of the modem features.

* MODULATION: FM. Audio applied direct to TX varactor. +/- 3 kHz deviation gives RF spectrum 20 kHz wide (-60db). Fits standard channel easily.

* 'IX MODULATOR: 8 bit long digital F.I.R. transversal filter in Eprom for transmit waveform generation (12 bit optional). Gives "brick-wall" audio spectrum. Typically -6 db at 4800 Hz, -60 db at 7500 Hz. Allows compensation for receiver (the channel) to achieve perfect RX "eye" . Up to 32 TX waveforms, jumper selectable. Output adjustable 0-8v pk-pk.

* SCRAMBLER (Randomiser): 17 bit maximal length LFSR scrambler, as per K9NG system, and UoSAT-C. Jumper selectable Data or BERT (bit error rate test) mode.

* RX DEMODULATOR: Audio from receiver discriminator, 50mv-10vpk-pk. 3rd order Butterworth filter, 6 kHz. Data Detect circuit for use on simplex (CSMA) links. Independent unscrambler.

* CLOCK RECOVERY: New digital PLL clock recovery circuit with 1/256th bit resolution. Average lock-in time 50 bit6 (depends on SNR).

* CONNECTS to Ax.25 TNC "Modem disconnect" jack. Suitable for TNC-2 (and any other provided the internal modem can be bypassed). Standard TNC digital connections needed: TXData, TXClock (16x bit rate), RXData, Data Detect ("DCD"), GND, (RXClock available). TTL levels. RADIO: TXAudio, RXAudio, GND. All connection6 via 0.1" pitch pads for SIL connectors or direct soldering Unwired DIN 41612 96-way connector (use optional).

* POWER CONSUMPTION: 10 to 15v DC at 40ma (CMOS Roms), 170ma (NMOS Roms). Total 19 ICs (13 CMOS, 2 DACs, 2 op-amps, 2 Eproms). 5 volt regulator and heatsink.

* OTHER FEATURES: The only set-up is TXAudio level. Channel calibration facility. Audio loopback. No hard-to-get parts.

* PCB: 160x100mm (single Eurocard format). Top professional quality, double sided, maxcopper ground plane, plated through, solder resist, yellow silk-screen. Four 3.3 mm mounting holes.

APPLICATION - TNCS

This modem is obviously only suitable for a TNC if it6 internal modem can be bypassed, and if it provides for the TTL digital signals:

* TXData	e.g. TNC-2 J4-19
* TXClock (16x bit rate)	J4-11
* RXData	J4-17
* Data Detect ("DCD")	J4- 1
* GND	J4-15
* RXClock (optional)	not used

TAPR TNC-2 based designs do this, typified by the TNC-2, PK-80, MFJ1270, TNC-200. Close relatives (but with minor variations) are Tiny-Z, Euro-TNC2C, BSX-2, PK-87, F'K-88 and TNC-220. The necessary interface is at the "Modem Disconnect Jack".

The modem's use is not confined to TNCs, however. Some of the recent multiport packet switches, indeed any digital signalling system, is suitable if it can service the minimum signal set above.

APPLICATION - RADIOS

The ideal would be to have a flat DC-8 kHz radio link. The "better" the TX and RX specification, the better the received data at the detector, and hence less suceptibility to errors.

Some apparently horrid receiver responses still offer useable service, but with a typically 3 db reduction in performance. A good radio achieve6 about 1.5 db implementation loss (compared with a perfect link).

Remember that one is pushing most radio6 to their limit since they were designed for speech where even 100% distortion is still intelligible. A little more finesse is required for data transmission.

RECEIVERS

* NBFM design
* Output from discriminator (essential)
* Response to DC (essential)
* Response no worse than -4 db at 4.8 kHz
* No worse than -10 db at 7.2 kHz
* As smooth/flat a phase delay a6 possible
* As smooth an amplitude response as possible
* Little change in response with 2 kHz de-tuning off-channel
* Symetric, linear FM discriminator characteristic

On the whole, most receivers will perform as required. Those with the least complicated IF filtering appear best, especially with type "D" 20 kHz channel filters (e.g. CFM455D), though the "E" (16 kHz) is OK too.

Radios with dozens of cascaded tuned circuit IFs tend to be fussy, and should be carefully aligned for even response, decent linearity, phase delay and mistuning performance.

TRANSMITTERS

* MUST generate true FM
* Response DC to 7.2 kHz flat (essential)

Transmitters based on Xtal oscillator/multipliers are likely to be the most appropriate. (Usually Base stations". So who wants to tie up a multimode radio anyway!)

Transceivers (synthesised or not) that have quite separate oscillator sub-system6 for generating FM and possibly SSB/CW, which is then mixed with a synthesised source to produce the final carrier am OK.

Simpler synthesised FM transmitters, where the varactor modulated oscillator is within the synthesis PLL are generally not useable, as the PLL tracks the modulation, and so you get no LF response. Them are ways around this by modulating the reference xtal too, but ...!

Remember you need true EM, which preferably means a varactor diode pulling the oscillator frequency, NOT phase modulating a tuned circuit.

9600 BAUD MODEM - DESCRIFTION

All the bits and pieces required to interface digital data to a radio are called a "modem", short for modulator/demodulator. These two functions are complementary, and essentially separate even though there may often be shared parts such as clocks and power supplies etc. Figure 1 is the full circuit diagram of production boards, issue 3. (Issue 1 were prototypes, issue 2 the beta-test models).

TRANSMIT RANDOMISER/SCRAMBLER

Data for transmission is first passed through a randomiser or scrambler. This ensures that there are no long runs of all "1"s or "0"s or repeated patterns. There are several good reasons for doing this. (Ref 2)

One is that the channel is not DC coupled.' It could never be so in an FM system unless one could guarantee both transmitter and receiver were always on frequency and had no drift. As this is virtually impossible to achieve, one simply AC couples the channel, i.e. gives it a response down to a few Hz, and exploits the feature of the randomised data that it has a negligible "DC" component.

Secondly, since the data stream is now randomised, its spectral energy is evenly spread out at all times. Intense spectral lines do not suddenly appear and create sporadic splatter into nearby channels

A third reason is that since the data is guaranteed to have a regular supply of ones and zeros, the receiver's bit clock recovery and demodulation circuits work better.

Not suprisingly a burst of data sounds like a burst of noise, and is quite hard to distinguish by ear from the unsquelched background.

TRANSMIT WAVEFORM GENERATOR

The transmit waveshape(s) are stored in an EPROM. An 8 bit shiftregister contains the most recent bits, which are used to look up a profile for the middle one. Four samples/bit go to make up the profile. In this way the transmitted waveform is synthesised not only from the present bit, but four that preceded it, and four to come.

The 8 bit value output from the EPROM is converted to a voltage by an inexpensive single-rail DAC, and is then analogue low pass filtered to remove harmonics of the clock and associated discrete phenomena. This is variously called "anti-aliasing", "smoothing" or "interpolating". Either way, it "joins up the dots"!

The arrangement as a whole is a "finite impulse response filter" or FIR for short.

The Transmit EPROM is normally a type 27C128 and can hold between 16 eight-bit long FIRs, to one 12-bit long FIR or various combinations. A 27C256 can also be used, offering up to 32 responses. NMOS roms are also suitable.

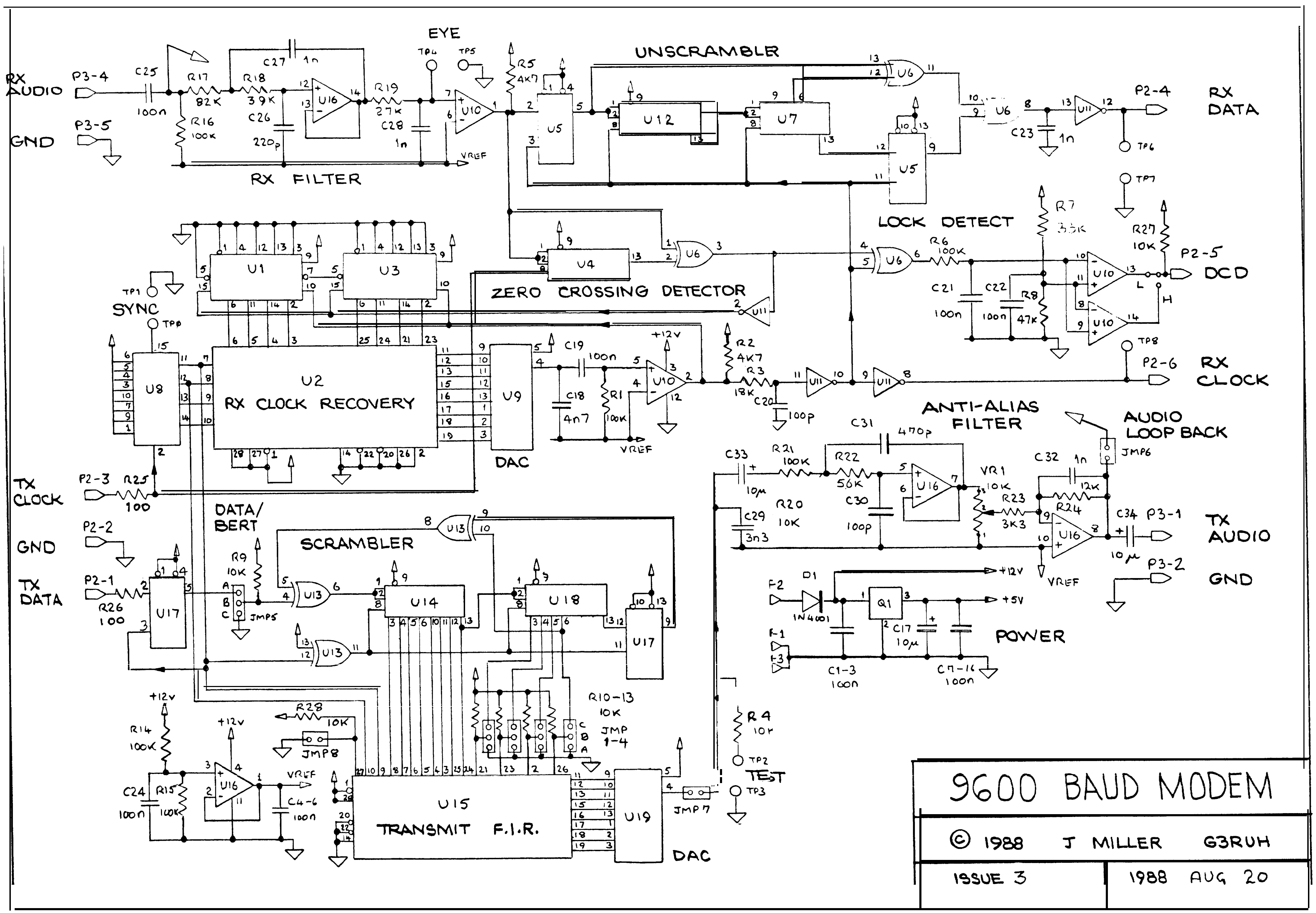
MODEM RECEIVE - FILTER/DETECTOR

Audio from the receiver discriminator is passed through a gentle input filter which removes out of band spurious noise, particularly IF residue. The signal is then limited and detected by sampling at the correct instant.

UNSCRAMBLER

The detected data, still randomised is then passed through an unscrambler where the original data is recovered, and this goes off to the TNC. A scrambler is very simple, consisting of a 17 bit shift register and 3 Exor gates. (See ref 2, fig 3).

The scrambling "polynomial" is 1 + X^12 + X^17. This means the currently transmitted bit is the EXOR or the current data bit, plus the bits that were transmitted 12 and 17 bits earlier. Likewise the unscrambling operation simply EXORs the bit received now with that sent 12 and 17 bits earlier. The unscrambler perforce requires 17 bits to synchronise.


RX FILTER
EYE
UNSCRAMBLER
RX DATA
DCD
LOCK DETECT
ZERO CROSSING DETECTOR
RX CLOCK RECOVERY
RX CLOCK
SYNC
DAC
ANTI-ALIAS FILTER
AUDIO LOOP BACK
TX AUDIO
SCRAMBLER
DATA/BERT
POWER
TRANSMIT F.I.R.
TEST
RX AUDIO
GND
TX CLOCK
TX DATA
9600 BAUD MODEM
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This polynomial was deliberately chosen to be the same as implemented by Goode (ref 1) in an earlier modem design. It will also be used on one of the UCSAT-C satellite downlinks.

B.E.R.T. TESTING

A particularly useful by-product of scramblers is "bit error rate testing", or BERT for short. Suppose the transmitted data is held to all "1"s. Then a receiver's error-free output should also be all "1"s, even though the transmitted data is quite random. So to test the quality of a link one merely sends all "1"s, and attaches a counter at the other end.

If one bit is corrupted due to channel noise, the error will in fact appear exactly 3 times at the receiver output, because there are 3 versions of the scrambled stream exored together. Even though one error creates two more, this doesn't matter because just the single error is enough for a packet to be rejected.

Incidentally, randomisers/scramblers don't really violate rules concerning codes and ciphers any more than do ASCII, Baudot or Morse. Since the scrambling algorithm is freely published, the meaning of the data is not obscured.

RECEIVE CLOCK RECOVERY

The demodulator must extract a clock from the received audio stream. It's needed to time the receiver functions, including the all-important data detector.

The familiar TAPR TNC-2 state machine is not satisfactory in this application, as its resolution is only 1/16th bit. It can show jitter up to +/- 5/16 ths of a bit in this narrow-band application, which gives bad performance for detector timing.

This modem uses a new digital phase locked loop (DPLL) with a resolution of 1/256th of a bit.

The received audio is limited, and a zero crossing detector circuit generates one cycle of 9600 Hz for each crossing (a proto-clock). This is compared with a locally generated clock in a phase detector based on an up/down counter. The counter increments if one clock is early, decrements otherwise. This count then addresses an Eprom in which 256 potential clock waveforms stored, each differing in phase by 360/256 degrees. In this way the local clock slips rapidly into phase with that of the incoming data.

RX Clock lock-in time depends on the signal to noise ratio, and the initial phase error. A signal that's already in phase pulls into lock in within 0 elapsed bits! A noise free signal exactly out of phase will pull in to the point where data errors cease within approximately 80 bits. A very noisy signal could take up to 200 bits. In practice an average figure is around 50 bits, or 5 ms at 9600 baud.

Proto-clock and local clock are also compared in an exor gate, and when they are "in-phase", a Data Carrier Detected signal (DCD) is sent to the TNC. High or low options are available.

TRANSMIT WAVESHAPE SYNTHESIS

As mentioned, a strength of this modem is its digital generation of the transmit audio waveform. The precise shaping compensates exactly for the amplitude and phase response of the receiver. It also allows very tight control of the transmit audio bandwidth.

The waveform is synthesised as follows. First the "ideal" receiver output waveform (at the "eye point") is defined. This waveform, for one isolated bit, has a perfect "eye". It has a value of +1 at T=0. and a value of 0 at +/-T, +/-2T etc where T is a bit period. Its spectrum is flat to 3300 Hz, -6db down at 4800 Hz, and is absolutely band limited to 6300 Hz. The waveform is called a "Nyquist Pulse".

Next the channel frequency and phase response is measured. It is made up of several parts; the modem transmit anti-alias filter, the radio transmitter response, the receiver response and finally the modem receive filter. In practice most of these components are already characterised, so it's only necessary to measure the radio receiver explicitly.

Now the ideal Nyquist pulse's frequency response is divided by the channel frequency response to give the ideal transmit spectrum. This is then Fourier transformed to the time domain, and specifies EXACTLY the waveform of a transmitted bit that would pass right through the system to emerge with the desired Nyquist shape.

This desired waveform will have a time span of some 15 bits or more duration. However, only the middle part of 8 to 12 bits duration will have significant amplitude. So the extremes are gracefully smoothed off to exactly 8 bits span, a process known as "windowing".

As a verification check, the pulse is now "sent" mathematically forwards through the channel to assay the effect of having to truncate it, and the "eye" point vertical jitter calculated. It is typically +/- 10% of a unit bit amplitude.

This calculation only defines a waveshape for one isolated bit. But it will extend over about 8 bits elapsed time. So the final stage in the synthesia is to add up the impulse responses of all 256 possible combinations of preceding and trailing bits to give the true "convolved" waveform that is finally used. The waveform is then stored as numbers in an Eprom.

The software to do the equalisation is programmed in Basic, except for the Fourier transforms (512 point complex FFTs) which are machine coded for speed. The waveforms and spectra are displayed graphically at every stage. Figure 2 illustrates equalisation of a fairly extreme specimen of radio, a Midland 13-509 220 MHz transceiver (USA).

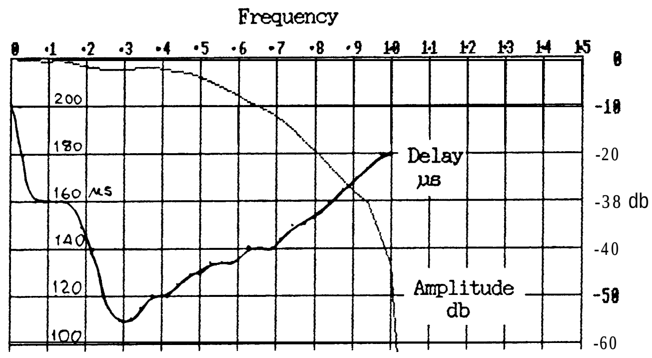

Fig. 2a. Frequency response and phase delay of a typical NBFM receiver. Note that the frequency axis is normalised. f = 1.0 corresponds to 9600 Hz.

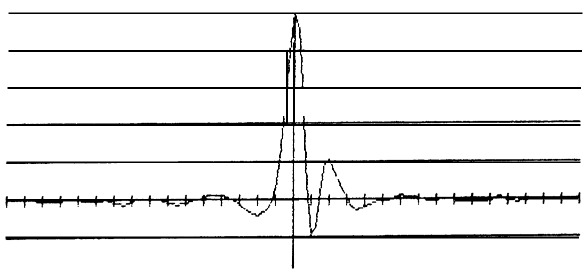

Fig. 2b. Impulse response corresponding to fig 2a. Horizontal axis time "ticks" are at intervals of 1 bit (1/9600 sec), and has been shifted some 125 µs so as to centre the peak. An isolated, unequalised bit would emerge from the receiver shaped like this. A stream of bits would be the sum of many of these. Bad fatures such as significant non-zero values at T = -2, +1 and +2 bits would give rise to substantial inter-bit interference and a very poor eye, making error free communication impossible. The purpose of equalisation is to eliminate this phenomenon.

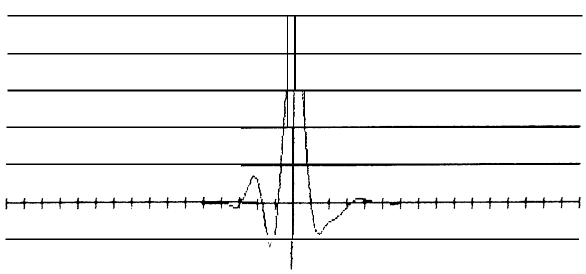

Fig. 2c. Equalised Transmit Bit. If the transmitter sends an isolated bit shaped like this, the receiver will give an output like fig 2e. This is the transmit waveform shaping for one isolated bit. If this corresponds to a binary "1", a binary "0" is a negative pulse like this.

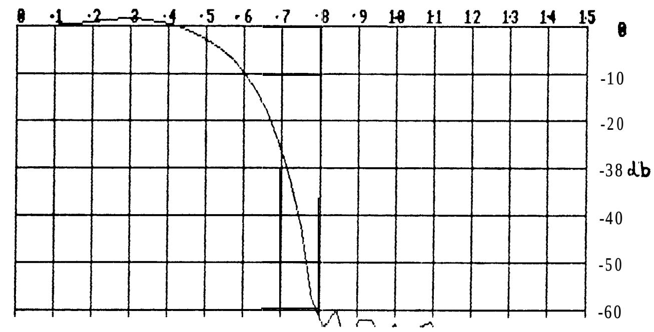

Fig. 2d. Spectrum of the transmitted audio pulse of fig 2c.

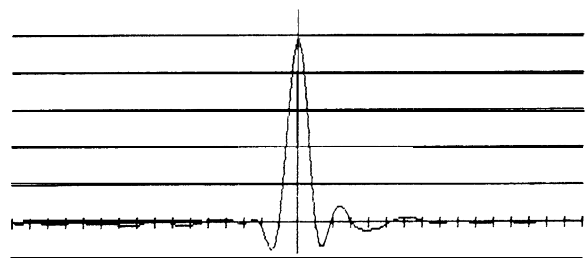

Fig. 2e. Receiver output response to an isolated bit which has been properly equalised. Note that generally zero crossings at the bit ticks (excepting T=0) are zero. This is a "Nyquist Pulse". In fact equalisation is not perfect (e.g. at T=4). This is due to the fairly extreme radio response chosen for illustrative purposes.

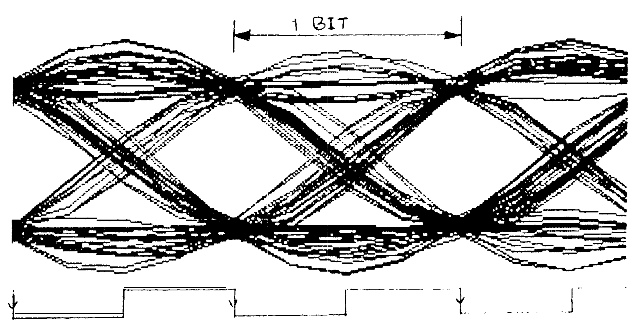

Fig. 2f. The convolution of many bits of fig 2e superimposed looks like this, an "EYE" diagram showing a few hundred bits over 3 bit periods. You would see this on an oscilloscope. The data detector samples this waveform at the widest part of the eye. See how as a result of equalisation the eye is wide open, giving maximum noise immunity. Vertical spread at the sample point is mainly due to the aberration at T = 4 in fig 2e. Note also the considerable spread in zero crossing instants typical of narrow bandwidth systems, which lead to the need for careful clock recovery circuit design.

PERFORMANCE

Users accustomed to the speed of a typical 1200 baud packet channel are usually astonished to see 9600 baud data via radio scrolling off the screen at full speed.

In the perfect environment of audio loopback, the error performance of the modem has been measured, and the implementation loss is about 1 db. In other words the modem itself does not introduce significant degradation in system peformance.

On the other hand it is not very appropriate to describe the modem performance quantitatively in terms of microvolts at an FM receiver input. So much depends on the particular model, and the individual specimen, the environmental noise level, frequency drift, and goodness of equalisation. Steve Goode (ref 1) has given detailed results for one typical situation, and it should be clear from this that there can be no simple snap performance measure, other than "does it work?".

What can be said is that once the received signal strength puts the receiver output above the "spitching" threshold, and into smooth noise, (and that's only a 1 db spread in RF level!) the 9600 baud system becomes essentially error free. So a radio link needs to be just over the noise threshold for good performance. (c.f. 1200 baud AFSK).

Remember, the purpose of this modem is to provide a reliable high speed communications facility - not to scrape weak DX off the noise floor!

EPROM SERVICE

The "standard" transmit Eprom contains waveforms for 16 (or 32) named receivers. One of these is almost certain to be satisfactory for an arbitrary receiver. If not, the author offers a customisation service. Full details are included in the modem Instruction Booklet. New receivers will gradually be added to the standard Eprom as users supply more data.

PCB AVAILABILTY AND SUPPORT

This project is supported with a Printed Circuit Board and full instructions. At the time of writing (88 Aug 16) some 200 are in worldwide use. The board and Eproms may be obtained in various ways:

1. Direct from the author: PCB £18 post paid UK/Europe, £19 airmail USA and elsewhere. TX and RX Eproms (programmed), when ordered at the same time as the PCB, £6/pair. Any eproms ordered separately £5 each. You are welcome to copy the eproms if you wish. Cheque, Eurocheque, Bank draft or cash. Sterling only, no credit cards.

2. From: PacComm Packet Radio Systems Inc, 3652 West Cypress Street, Tampa, FL 33607-4916, USA

3. From: TAPR, PO Box 22888, Tucson, Arizona 85734-2888, USA.

4. From: Siskin Electronics, PO Box 32, Hythe, Southampton, S04 6WQ, England.

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Scores of people have provided feedback and support for this project. These include some 20-25 beta testers world-wide who provided many responses for the eproms, design criticism, and debugged all those wretched non-standard "standard" modem disconnect headers! Gwyn Reedy W1BEL of PacCom Inc and Phil Bridges G6DLJ of Siskin Electronics have been instrumental in promoting the design at both amateur and commercial levels. I also acknowledge the pioneering work of Steve Goode K9NG who did a lot of spade work some years ago, and which convinced me all along that this project was on sound ground. Thanks to Bob McGwier N4HY o.b.o. TAPR for insisting this design should see the light of day and not remain the secret weapon of EastNet-UK's links.

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