INTRODUCING THE PACKET ADAPTIVE MODEM (PAM)

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Abstract

This paper describes a modem design undertaken by Robert E. Watson and the author. The modem was designed primarily for high-frequency packet radio applications. It operates at signaling rates of 75, 150, 300, 600 and 1200 bauds. The data rate is software controllable through a modified RS-232-C port. A frequency shift of 600 Hz is maintained for all data rates. The modulator is phase continuous and provides X32 or X64 clock to the packet assembler/disassembler (PAD) or terminal-node controller (TNC). The demodulator employs a National MF10 switched-capacitor filter (SCF) chip for each of the 1500-Hz mark and 2100-Hz space frequencies. Bandwidths of the MF10s are software controllable to accommodate different received data rates and receiver frequency tolerances. A point-to-point wired prototype of the modem has been built on an S-100 perf board. Power may be taken from the S-100 bus or provided by a separate power supply. The prototype has been laboratory tested with excellent "eye diagrams" on speeds up to 600 baud with some eye closing at 1200 baud. Still pending is a design decision whether to combine an optimal minimum-shift keying (msk) demodulator circuitry for 1200-baud operation with this modem or to make it a separate modem. Upon completion pc boards and documentation will be made available to amateurs.

Baudot Radioteletype - Some Background

High-frequency (hf) radioteletype (RTTY) using frequency-shift keying (fsk) began in the U.S. Amateur Radio Service in 1953 when the Federal Communications Commission (FCC) authorized F1 emission in the hf bands. Virtually all teletypewriters at that time were military or commercial surplus. They used a version of a five-unit code (U.S. Military Standard or CCITT International Telegraphic Alphabet No. 2) usually referred to as the Baudot or Murray code. Five-unit teletypewriters used since the 1950s in the U.S. normally operated at a speed of 45.45 baud (60.61 wpm), but a few 56.92-baud (76.68-wpm) and 74.2-baud (100-wpm) machines were also used. Machines available from European sources ran 50 baud (66.67 wpm).

Many fsk demodulators (also called "tuning units" or TUs) were home-brewed by amateurs. However, the design standards were those of military and commercial RTTY demodulators. In the 1950s, the demodulators were normally designed to receive two audio frequencies separated by some multiple of 170 Hz, usually 850 Hz. The favorite frequencies for many years were 2125 (mark) and 2975 Hz (space). In time, amateurs experimented with narrower shifts, particularly 170 Hz, using the audio frequencies 2125 (mark) and 2295 Hz (space), and standardized on it in the late 1970s. Today, virtually all amateur Baudot RTTY demodulators use 170-Hz shift, although many also accommodate 850-Hz and 425-Hz shifts as well. Many hf RTTY stations use transceivers in the ssb mode, sending afsk into the microphone input of the transmitter and obtaining afsk output from the receiver audio stages. Many of these transceivers start rolling their audio off not much above 2000 Hz. As a result, the afsk frequencies 1275 Hz (mark) and 1445 (space) (called the low tones) are also used and are standard in Europe.

The majority of these afsk RTTY demodulators were designed as fm demodulators. In this type of demodulator, the signal is first sent through a bandpass filter to remove out-of-band interference and noise. It is then limited to remove amplitude variations. The signal is fm-demodulated in a discriminator or a phase-locked loop (PLL). The output of the detector is run through a low-pass filter to remove noise at frequencies above the baud rate. The result is fed to circuit which makes the decision between binary 1s and 0s.

ASCII Radioteletype

Effective March 17, 1980 FCC rules authorized the use of the American Standard Code for Information Interchange (ASCII) as defined in American National Standard Institute (ANSI) Standard X3.4-1968.

Straightforward asynchronous serial ASCII has not been very popular on the ham bands since it was legalized. This is due to a variety of reasons. Some RTTYers own mechanical teletypewriters, mostly 45-baud Baudot. They currently are being phased out in favor of electronic digital terminals or computers which can communicate in either Baudot or ASCII. AMTOR is now added to the list of modes possible with "glass TTYs."

Probably the reason why ASCII has not caught on in the hf bands is that some amateurs have experienced poor results trying to operate 300-baud ASCII. The lack of success is largely due to the modem design limitations.

In order to operate existing Baudot demodulators at the higher signaling rates used in ASCII, it is necessary to raise the cut-off frequency of the low-pass filter, and it may be necessary to redesign the bandpass filter and any filters used in the detector. The design can usually be stretched to copy 113 bauds. However, poor results can be expected when trying to modify most 170-Hz, 45-baud demodulators to receive signaling rates above 110 bauds.

Other problems inlcude intersymbol distortion due to multipath propagation. Multipath can be reduced or eliminated by operating near the maximum-usable frequency (muf). These problems are discussed in my paper given at the first packet conference.[RIN81]

Amateur ARQ and FEC hf RTTY Systems

Although hf skywave RTTY is difficult, high-quality error-free operation has been achieved by two robust systems using automatic repeat request (ARQ) and forward error control (FEC). One is AMTOR.[MAR81], [FCC RM-41 22], [MEI82] Another experimental system was designed by Jerome Dijak, W9CD.[DIJ81-83]

Amateur Hf Packet Experiments

Here is a summary of U.S. amateur hf packet experimental contacts:

On February 8, 1982 K1RT in Connecticut and W9LLO in California made a brief connection over 20 meters using Collins KWM-380s, Vancouver TNCs and hf RTTY modems.

On May 31, 1982, K8MMO and W4RI, both in Northern Virginia, carried on a two-hour connection on 13 meters, at 1200 bauds, using ICOM IC-701's, Vancouver TNCs and Bell 202 modems.

On October 16, 1982, a 15-minute connection took place between W3IWI in Maryland and and N5AHD in Texas using Vancouver TNCs and Bell 202 modems.

Design Considerations

Data Rates

For this modem design, we are primarily concerned with signaling speeds which are feasible for passing through unmodified audio sections of Amateur Radio transceivers, particularly hf-ssb transceivers.

The FCC rules permit up to 300 bauds on frequencies between 3.5 and 21.25 MHz, up to 1200 bauds between 28 and 50 MHz, 19.6 kilobauds between 50 and 220 and 56 kilobauds above 220 MHz.

In addition to the regulatory restriction, the upper signaling rate may be limited on hf skywave due to intersymbol distortion introduced by multipath propagation. This and related subjects were analyzed in a paper I presented at the first packet conference in 1981.[RIN81] For some general rreading on the behavior of the hf skywave medium for data communications see [BRA75].

Speeds up to 1200 bauds should be practical on the hf amateur bands whenever a usable frequency exists near the maximum usable frequency (muf). At present, use of a 1200-baud signaling rate below 28 MHz requires a Special Temporary Authority (STA) from the FCC. I plan to apply for an STA in the near future. I also plan to investigate the feasibility of a permanent rules change to permit up to 1200 bauds on all hf bands, including a portion of the 160-meter band where F1 emission is not now permitted.

At the lower end of the speed range, some consideration was given to including the rate of 37.5 bauds for those infrequent occasions when 75 bauds can't be made to work due to intersymbol distortion. The speeds of 18.75 and 9.375 bauds could have been included but were rejected as being too slow.

We decided to make the speeds 75, 150, 300, 600 and 1200 bauds. These five speeds are selected by means of on-board solid-state switches. The modulator clock output rate is controlled by a 4512 8-channel buffered data selector. Filters in the demodulator are set by six 4051 single 8-channel analog multiplexer/demultiplexers. These seven chips are controlled by three lines from the PAD.

Using five speeds and having an 8-channel switching capability permitted the inclusion of wider bandwidths for the three slower speeds of 75, 150 and 300 bauds. The wider-bandwidth capability is to make allowance for frequency error. This is particularly useful when the receiver's frequency is digitally controlled and/or left unattended. The ICOM IC-720A is subject to a frequency error of ±50 Hz when externally controlled. On the other hand, a no-compromise narrower bandwidth can be selected when the receiver is front-panel controlled, thus settable to within ±5 Hz.

Frequency Shift

The 170-Hz shift in common use for Baudot RTTY could be used for data rates of 75 and 150 bauds with signal-to-noise (S/N) ratios common on amateur hf RTTY. Use of this shift at 300 bauds has been done with some sacrifice of demodulator error performance. It is not suitable for the speeds of 600 and 1200 bauds.

When the narrower shifts (say below 400 Hz) are used, there is a tendency for the mark and space frequencies to fade dependently (together). So, if one fades, the other is likely to fade at the same time. The mark and space frequencies tend to fade more independently when the shift is wider. Independent fading is common at the age-old shifts of 425 and 850 Hz, with more independence obseved for 850 Hz shift. Some commercial RTTY demodulators make use of this so-called in-band frequency diversity and use combining and/or selection techniques to continue copying even if one frequency or the other fades completely.

We have chosen a shift of 600 Hz for two reasons. One is that there is enough frequency separation to permit good in-band frequency diversity action. Also, the frequency of 600 Hz is directly related to the baud rates and permits phase-continuous modulation and synchronous demodulation. At 1200 bauds, a 600-Hz shift is called minimum-shift keying (msk) or sometimes fast frequency-shift (ffsk) to connote that the shift is less than 1 Hz per baud.

Physical Construction

We decided to use an (IEEE 696) S-100 card for the modem. This 5- x 10-inch board was about the size needed for all the chips if a double-sided printed wiring is used. The modem can be plugged into an S-100 computer frame and take power from the bus. Or it can be mounted in its own box with a separate power supply if desired. None of the S-100 data or control lines is used.

Having tasted the fruits of receiving RTTY with a polarization-diversity setup, I plan to build a second PAM board for the second demodulator channel. One demod will be fed by an IC-720A transceiver, the other by an IC-R70 receiver. I also just purchased an IC-7072 interface unit which slaves the two together. The first PAM will have the modulator and a demodulator. The second board is to have an identical demodulator (same pc pattern) and, in the place of the modulator, a diversity selector to process the outputs of the two demodulators.

Input/Output Connections

The (data) I/O connection to the PAD follows EIA RS-232-C rules with the exception that the three data-rate control lines (pins 18, 23 and 25) are presently at TTL levels to reduce the PAD chip count. Insulation-displacement connector (IDC) headers are used on both the PAD and PAM boards rather than the bulkier DB-25. If there is need to route this I/O outside the cabinet, a cable with an IDC plug would connect to a back-panel-mounted DB-25.

The (analog) I/O connection to the radio is to be done with an IDC header. Work remains to be done on the radio side of the modem to ensure compatibility with various amateur hf radios. The goal is to devise an interface scheme that will permit the greatest flexibility.

The interfacing of the transmited analog (TxA) and received analog (RxA) signals is only a matter of adjusting levels and keeping unwanted rf at arm's length. However, the IC-720A and the IC-R70 (and some other ICOM radios) have a 24-pin accessory connector which permits digital remote control of frequency. As some external control circuitry is needed for the ICOMs, one of my future projects will be to design a Receiver Interface Board (RIB) to go between the modem and the radio(s) when ICOMs are used. The RIB will also be built on an S-100 card. As the RIB will be optional, the connector scheme will be designed to work with the RIB or without it.

The I/O design has been deferred until receipt of a Tuscon Amateur Packet Radio (TAPR) beta test model TNC. Although designed as a companion modem for the AMRAD PAD, the goal is to make the PAM usable with the preexisting Vancouver and TAPR TNCs before the I/O design is finalized.

Circuit Description

Fig. 1 shows the shematic of the PAM as of this writing. CMOS logic integrated circuits are used throughout.

Modulator Circuitry

A 2.688-MHz crystal master clock feeds two divider chains. This crystal is not on a stock frequency and was ordered from a crystal manufacturer.

The U2-U6 chain divides by 32, then divides by 7 for mark or 5 for space. U4 divides by 8 and feeds its outputs to two U5 Ex-OR gates to produce a stepwise approximation of a sine wave at either 1500 Hz (mark) or 2100Hz (space). The U6 active filter removes the steps to produce a nearly sinusoidal output to modulate the transmitter.

The other divider chain produces either X64 or X32 clock for the PAD or TNC respectively for the signaling rates of 75, 150, 300, 600 and 1200 bauds. The U9 binary counter delivers a number of outputs which correspond to X64 clock at each rate. These outputs are selected by U10. A divide-by-2 counter of U4 is used for an X32-clock output.

Demodulator Circuitry

A commonly stocked 2.097152-MHz crystal was used as the master clock to 49.94 times the center frequencies of the two MF10 filters. This stock crystal (and divider chain) just happens to clock the MF10 filters for center frequencies of 1499.8 and 2099.7 Hz.

U109 is the MF10 space filter, U110 the mark filter. Both sections of each MF10 are used to achieve a 4th-order bandpass filter with steep skirts to cope with hf band crowding. Four 4051 8-channel analog multiplexers, U105-U108, select resistance values which set filter bandwidths.

The first halves of U111 and U112 are active low-pass filters for the mark and space tones and provide feedback to the MF10s to reduce tilt. The other halves are full-wave detectors.

The first half of U113 sums the detected outputs and does some low-pass roll off. The main post-detection low-pass filtering is accomplished in the second half of U113 with U114 and U115 there to switch resistor values according to baud rate. U116's two halves are positive and negative peak detectors.

One half of U117 is a comparator for the positive and negative levels and feeds the RxD to the PAD via part of U5 which can be used to invert data. Inverting data is not necessary when NRZI encoding is used but may be needed for NRZ-encoded signals.

The other half of U117 is a tuning indicator circuit. An on-board LED is switched in for testing and out when an external LED is connected. Here's how to use it: While tuning the receiver, control the input level (RxA) for less than half brightness. Tune for maximum brightness, reducing the receiver gain as necessary. Increase the input signal level until a maximum is reached, then back it off to half brightness.

Of course, an oscilloscope would provide a better tuning display. One can be connected at points X and Y fed by the first halves of U111 and U112.

Semiconductors

Q1	2N2222	npn transistor
U1,101	CD4049	hex inverting buffer
U2,9,102	CD4024	7-bit binary counter
U3,7,8,103,104	CD4029	presettable binary/decade up/down counter
U4	CD4520	dual binary counter
U5	CD4077	quad ex-OR
U6	LM741CN	op amp
U10	CD4512	8-channel data selector
U11	MC1489	RS-232-C receiver
U12	MC1488	RS-232-C driver
U105-108,114,115	CD4051	single 8-channel analog multiplexer/demultiplexer
U107,108	MF10BN	universal monolithic dual switched capacitor filter
U111-113	MC1458	op amp
U116,117	TL082	op amp

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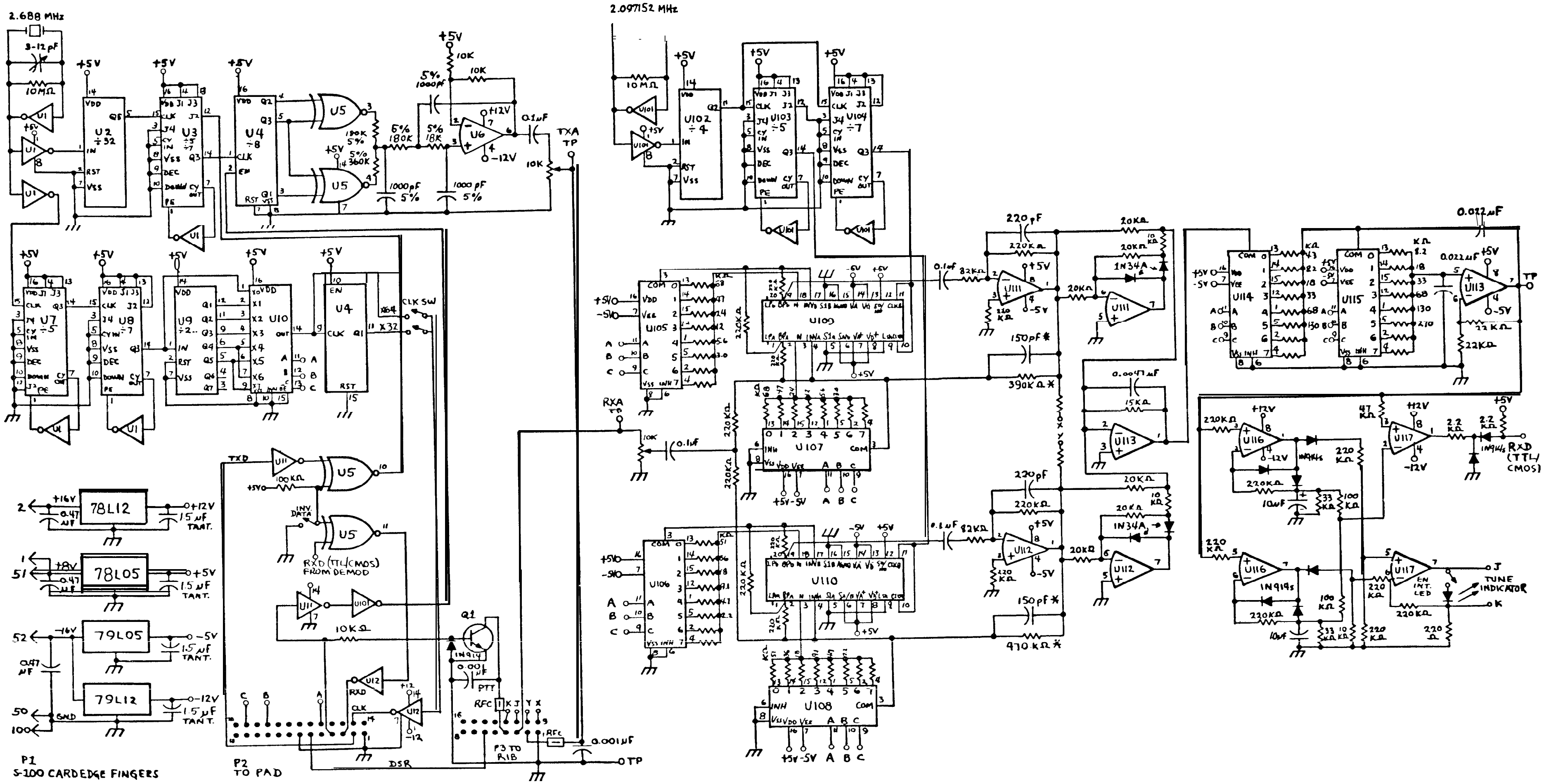
2.688 MHz
3-12pF
10MΩ
U1
U2 ÷32
U3 ÷5 ÷7
U4 ÷8
U5
U6
+12V
-12V
0.1uF
TXA TP
10K
1000pF 5%
5% 180K
5% 18K
180K 5%
5% 360K
U7 ÷5
U8 ÷7
U9 ÷2...
U10
CLK SW
X64
X32
TXD
100KΩ
INV DATA
RXD (TTL/CMOS) FROM DEMOD
10KΩ
Q1
1N914
0.001 uF
PTT
RFC
RXD
CLK
DSR
78L12
78L05
79L05
79L12
0.47 uF
1.5uF TANT.
+16V
+8V
-16V
+12V
+5V
-5V
-12V
GND
P1
S-100 CARDEDGE FINGERS
P2
TO PAD
P3 TO RIB
0.001uF
TP
2.097152 MHz
10MΩ
U101
U102 ÷4
U103 ÷5
U104 ÷7
RXA TP
U105
U106
U107
U108
U109
U110
U111
U112
U113
U114
U115
U116
U117
220pF
220KΩ
20KΩ
82KΩ
1N34A
150pF*
390KΩ*
470KΩ*
0.0047uF
15KΩ
0.022uF
22KΩ
1N914s
RXD (TTL/CMOS)
TUNE INDICATOR
INT. LED
10uF
J
K